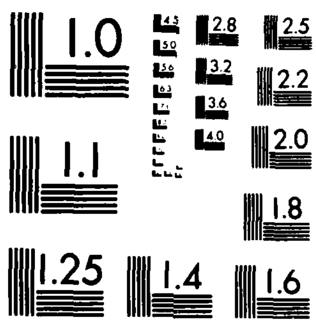
AD-A125 749 A STUDY OF WAVELENGTH DIVISION MULTIPLEXING FOR AVIONICS APPLICATIONS..(U) ITT ELECTRO-OPTICAL PRODUCTS DIV ROANOKE VA J C WILLIAMS ET AL. AUG 82 ITT-82-32-02 1/3

UNCLASSIFIED AFWAL-TR-82-1118 F33615-81-C-1481 F/G 9/3 NL

M-2



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFWAL-TR-82-1118

A STUDY OF WAVELENGTH DIVISION MULTIPLEXING FOR AVIONICS APPLICATIONS

J. C. WILLIAMS
ITT
ELECTRO-OPTICAL PRODUCTS DIVISION
7635 PLANTATION ROAD, N.W.
ROANOKE, VIRGINIA 24019

AUGUST 1982

FINAL REPORT FOR PERIOD 15 JUNE 1981 TO 16 AUGUST 1982

AVIONICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Robert Heuman

ROBERT HEUMAN
PROJECT ENGINEER

B.R. Altschuler LtCol USAF

LT COL B. ALTSCHULER
TECH MGR, ADVANCED RESEARCH GROUP
INFORMATION PROCESSING TECHNOLOGY BRANCH

FOR THE COMMANDER

Frank A. Scarpino

FRANK A. SCARPINO
ACTG CH, SYSTEM AVIONICS DIVISION
AVIONICS LABORATORY

"If your address has changed, if you wish to be removed from our mailing list, or if the addressee is no longer employed by your organization please notify AFWAL/AAAT, W-PAFB, OH 45433 to help us maintain a current mailing list".

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-82-1118	2. GOVT ACCESSION NO. AD-A125749	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A STUDY OF WAVELENGTH DIVISION MULTIPLEXING FOR AVIONICS APPLICATIONS		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 15 June 1981-16 August 1982
		6. PERFORMING ORG. REPORT NUMBER 82-32-02
7. AUTHOR(s) J. Williams, D. Porter, T. Leonard, S. Goodman, D. Huber, S. Vidula, G. Gasparian, J. Edwards		8. CONTRACT OR GRANT NUMBER(s) F33615-81-C-1481
9. PERFORMING ORGANIZATION NAME AND ADDRESS ITT Electro-Optical Products Division 7635 Plantation Road, N.W. Roanoke, Virginia 24019		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS P.E.62204F Project 2003 08 12
11. CONTROLLING OFFICE NAME AND ADDRESS Avionics Laboratory (AFWAL/AAAT) AF Wright Aeronautical Laboratories Wright-Patterson AFB, Ohio 45433		12. REPORT DATE August 1982
		13. NUMBER OF PAGES 240
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

The computer programs contained herein are theoretical and in no way reflect any Air Force-owned software programs.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fiber optics
Avionics systems
Wavelength division multiplexing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The performance of avionics wavelength division multiplexed (WDM) fiber optic systems was analyzed using an Optical Circuit Analysis Program (OCAP) developed during the study. Design solutions were found for several sets of Air Force avionics information transfer specifications, and sensitivity analysis techniques using OCAP were used to show that the solutions were reliable. Recommendations were made on key component developments which could result in major advancements in WDM system design. These developments would include diffraction grating WDM couplers, high speed-high power light emitting diodes, and pin-FET receivers.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. (continued)

Quantitative analysis of an avionics WDM system using these components indicates performance beyond that previously thought possible.

Three specified Air Force WDM avionics systems were designed which could be fabricated using technology available in the 1983-1985 time frame.

A design for a WDM demonstration system was developed which allows WDM systems to be demonstrated and WDM components to be tested. The WDM demonstration system was designed for laboratory bench applications and features a modular organization to provide for maximum user flexibility. Examples are given of the use of the WDM demonstration system for measurements of system performance parameters such as bit error rate, link delay, optical dynamic range, and rise time, and recommendations are made on key future component developments which could enhance avionic WDM systems.

SUMMARY

The performance of avionics wavelength division multiplexed (WDM) fiber optic systems was analyzed using an Optical Circuit Analysis Program (OCAP) developed during the study. Design solutions were found for several sets of Air Force avionics information transfer specifications, and sensitivity analysis techniques using OCAP were used to show that the solutions were reliable. Recommendations were made on key component developments which could result in major advancements in WDM system design. These developments would include diffraction grating WDM couplers, high speed-high power light emitting diodes, and pin-FET receivers. Quantitative analysis of an avionics WDM system using these components indicates performance beyond that previously thought possible. Three specified Air Force WDM avionics systems were designed which could be fabricated using technology available in the 1983-1985 time frame. Air Force system I, a four-wavelength, duplex, 100-Mb/s, point-to-point system, was designed using light emitting diode (LED) sources and pin detectors. Wavelengths selected in one direction were 800 nm and 900 nm; in the opposite direction, 1300 nm and 1550 nm were selected. Lensed dichroic couplers would provide the wavelength selectivity. Air Force system II, an eight-wavelength, codirectional, 300-Mb/s, point-to-point system, was designed using laser diode sources with channel wavelengths from 760 nm to 847.5 nm. Silicon pin detectors were used and diffraction grating mulitplex/demultiplex couplers were selected. Air Force system III, a 32-terminal, 2-wavelength, 20-Mb/s data bus, was designed using LED sources driving channels at 800 nm and 900 nm. Lensed dichroic couplers were used for wavelength selectivity and a transmissive star coupler was used for terminal distribution. Silicon pin photodiodes were selected as detectors for both channels.

A design for a WDM demonstration system was developed which allows WDM systems to be demonstrated and WDM components to be tested. The WDM demonstration system was designed for laboratory bench applications and features a modular organization to provide for maximum user flexibility. Operational modes of the system are (a) AETMS demonstration, (b) AETMS self-test, and (c) individual channel operation. Up to eight channels (eight wavelengths) can be supported by the system and bidirectional operation is possible for the proper selection of transmitter, receiver, and coupler modules. Mechanical packaging of the WDM demonstration system is based on modular transmitter, receiver, and coupler units which fit into rack-mountable cabinets. The AETMS, self-test, and power supply system parts were designed to be built into the cabinets. Electrical connections, source drive adjustments, and operating controls are located on front panel surfaces. Intermodule optical connections are made with single fiber jumper cables. Examples are given of the use of the WDM demonstration system for

SUMMARY (continued)

measurements of system performance parameters such as bit error rate, link delay, optical dynamic range, and rise time. Recommendations are made on key future component developments which could enhance avionic WDM systems.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

1.0 INTRODUCTION

This Final Technical Report is CDRL item number 11 of Air Force contract F33615-81-C-1481 and covers the time period 15 June 1981 to 16 August 1982. All contract effort is covered by this report and, of necessity, some previously delivered information is repeated in this document.

The central program objective, as contained in the contract statement of work (SOW), was "to establish wavelength division multiplexing (WDM) technology base line designs which can be used to satisfy current avionics information transfer requirements and still be extendable for use in future applications." The title of the reported work is "A Study of Wavelength Division Multiplexing for Avionics Applications." Specific avionics applications to be considered were defined in the SOW (attached as Appendix A) and the study was constrained to the use of components which would be available in the 1983-1985 time frame. Four major tasks were carried out under the contract to complete the required work. These tasks, which are sequentially discussed in the body of this report, were (a) technology survey, (b) base line systems design, (c) system sensitivity analysis, and (d) demonstration system design. The various tasks were led by senior level engineers and scientists specializing in the required areas.

Significant technical accomplishments were made by the program. The major accomplishment was completion of the first in depth quantitative study of avionics WDM systems. Previous work had concentrated on component performance or on simple two-channel WDM systems. The work reported in this document started with available component data and ended with quantitatively analyzed avionic system designs which have up to eight optical channels. The system performance calculations show that the optical links designed under this contract will function within specifications using currently demonstrated components. Overall avionics WDM system performance should improve using the superior components which are forecast to be available in the 1983 to 1985 time frame. Analysis of the study results led to a new concept for avionics WDM systems which takes advantage of diffraction grating couplers, high speed-high power light emitting diodes, and pin-FET receivers. The synergistic interactions of these components result in system design possibilities that address current design problems. Recognitition of these design possibilities was made possible by use of the "optical circuit analysis" computer programs developed during the study with the use of component data collected during the study. Quantitative considerations of the new system designs show that laser diodes and avalanche photodiodes (APD) can be eliminated in many cases where they were previously required. Recommendations concerning these new systems are made at the end of this report.

The WDM for Avionics Applications program was organized as illustrated in the rather complicated diagram of Figure 1.0-1. Program activities were divided into four areas:

a. Technology forecast

b. Conceptual system design

c. System sensitivity analysis

d. Demonstration system development

Figure 1.0-1 shows the detailed interactions between these activities and shows the approximate schedule on which the activities ran. The many interactions between activities were necessary to ensure that a cooperative combination of technical talent contributed to meeting the program objectives. The following sections of this report cover the individual activities, activity interactions, program conclusions, and recommendations.

23202

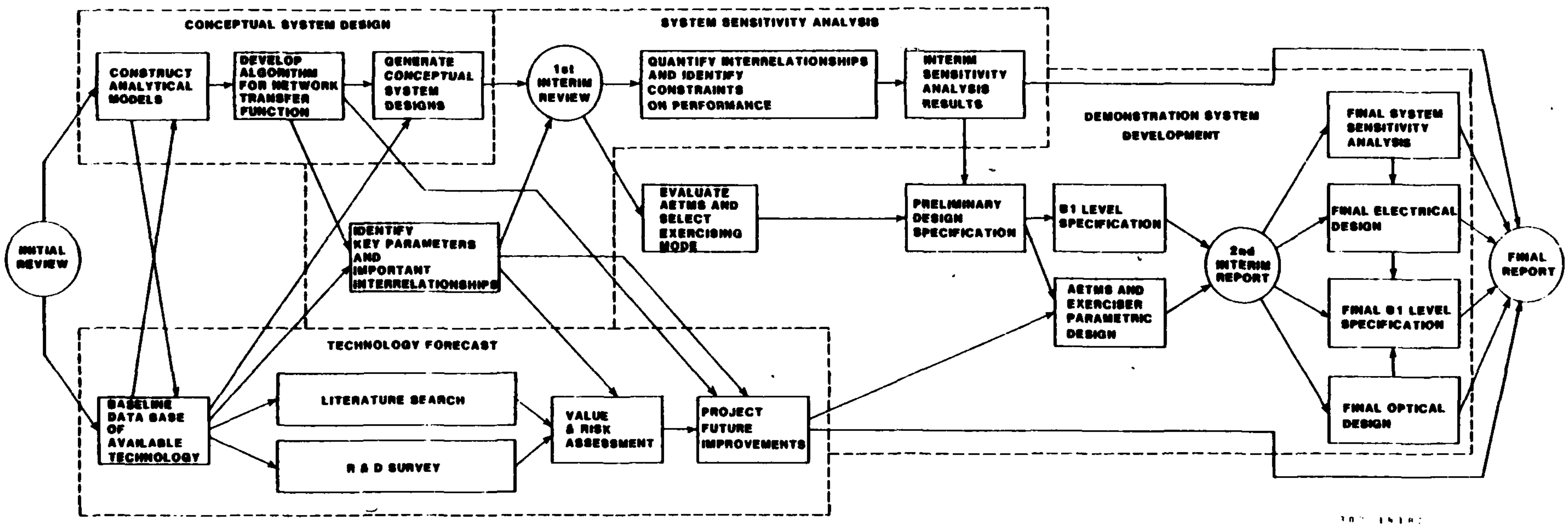


Figure 1.0-1. WDM Study Organization.

2.0 COMPONENTS AND TECHNOLOGY FORECAST

The purpose of the components and technology forecast task was "to identify component developments which could provide for improved/expanded capability in the 1982-1985 time frame." The identified component developments were to be used in the base line system designs. A literature search and an industry survey were the central elements of the components and technology task. The outputs of the task were component selections for systems use, component sensitivities for analysis purposes, a bibliography, an industry survey report, and a selection of possible component developments. The three subsections of this section cover in turn the literature search, industry survey, and technology forecast.

2.1 Literature Search

The starting point for the literature search was an extensive set of references on WDM collected at ITT EOPD over several years by a number of people. This material had not been formally organized nor had a formal search been made to ensure completeness. Both of these efforts were accomplished during the current investigation. Literature searches were made on WDM systems and components. Both "by hand" searches tracking down citations used in key reference papers were performed and computer data base searches were done using major technical data bases. The result of this effort was the bibliography included as Appendix D. This bibliography is an up-to-date, organized collection of the technical publications in the WDM field. All of these publications were reviewed for use in the current work.

2.2 Industry Survey

All manufacturers of fiber optic systems and components are aware of the future prospects of WDM technology and have plans, often proprietary, for developing WDM products. Fiber manufacturers, for example, produce "dual-window" fiber which has good performance at both short (~850 nm) and long (~1300 nm) wavelengths. To estimate the interest in WDM among the fiber optics industrial community, ITT EOPD contacted organizations identified as having or thought to have interests in WDM. The list of these organizations was drawn up using previously published surveys, promotional material, and personal knowledge. This list, organized by type of component, is included as Appendix B. The WDM components learned about through telephone contact with the listed organizations are listed in separate parts of Appendix B. This components list is known not to be complete because some manufacturers were not able to supply "absolutely up-to-date" information on their WDM products. Other manufacturers produce WDM products on a research and development (R&D) basis and could not be specific about components. Yet others had products "planned for release in the near future" and were unable to supply information in time for this report. In spite of these problems, the industry survey which was carried out was very useful. The survey showed that WDM is being taken seriously by the industry, most necessary components are available in small quantities now, and development is active on advanced WDM components. Examples of this situation are tightly specified laser diode and WDM coupler availability. These key components are produced on a custom basis now but several organizations have the capability of becoming large volume suppliers to WDM system builders as the demand grows. Reduction in costs of these key components and availability in a shorter period of time could be achieved by carefully selected development contracts. Paragraph 2.3 of this report mentions several areas which seem to be promising.

2.3 Technology Forecast

The technology forecast provided component selections for the Air Force base line system designs and suggestions for component developments which would be of use to WDM avionics systems. The technology forecast task also provided the detailed component data needed for the system sensitivity analysis of the base line designs. The key components, because of their wavelength selectivity, were sources, detectors, and couplers. Detailed descriptions of these components form the following subsections of this report. Optical cable and optical connectors, while they are major system components, do not have strong wavelength dependent performance when used in the short lengths required for avionic applications.

2.3.1 Sources

The optical sources appropriate for fiber optic avionics systems are injection laser diodes (ILD) and light emitting diodes. These sources must be chosen for a specific system based on coupled optical power, spectral emission, and projected reliability. Table 2.3.1-1 compares these sources in a qualitative way which is, in some cases, sufficient for initial selection for use in a WDM system. The general information in Table 2.3.1-1 more often can be used to exclude a certain source type from consideration in a specific system.

The short fiber optic system lengths which will be used in avionic systems diminish the effects of optical fiber attenuation and dispersion and allow wide latitude in the selection of system channel wavelengths. In principle, if the system fiber is free of major absorption peaks, channel wavelengths could be allocated from the visible part of the spectrum to the near infrared oxide absorption edge. The ILD and LED sources which operate in this spectral region are made of alloys of group III and group V elements doped with appropriate impurity elements and grown into various junction and waveguide-containing structures. The material composition of the active (light emitting) region determines the emission wavelength of the source.

Table 2.3.1-1. Source Candidates for Avionics WDM Systems.

Source Type	Advantages	Disadvantages
Injection laser diodes (ILD)	• High coupled power • Narrow spectral emission • High speed	• High temperature sensitivity • Spontaneous emission* • Suspect reliability • Cooling required • Poor availability of units meeting wavelength specifications • High cost
Light emitting diodes (LED)	• Low temperature sensitivity • Good reliability • Moderate cost • Good availability • Moderate speed	• Moderate coupled power • Wide emission spectrum • Speed/power trade off

*This is not a disadvantage compared with light emitting diodes but compared with a "perfect" laser.

AlGaAs laser diodes and light emitting diodes for fiber optic systems are commercially available between 800 nm and 900 nm. Recently, AlGaAs laser diodes (and light emitting diodes) with central emission wavelengths between 750 nm and 800 nm have been developed for video disc applications. Use of these devices allows a wider spectral range and, consequently, increased isolation between transmission channels or an increased number of operating channels. The AlGaAs technology has been developed to a high degree.

The second source wavelength regime is between 1200 nm and 1600 nm and utilizes InGaAsP technology. These devices are in active development and therefore have not reached the reliability and repeatability levels of the more mature AlGaAs technology. InGaAsP devices will remain developmental until high volume production is achieved.

The primary source parameters affecting system performance are

a. Modulation rate versus output power
b. Central wavelength tolerance
c. Spectral characteristics
d. Modal characteristics (laser diodes only)
e. Coupled power into the pigtail fiber

Since the output power of semiconductor sources is dependent on data rate, the modulation limitations of these devices must be known. The inherent modulation rate of semiconductors is dependent on the spontaneous carrier lifetime. The relative power response (P(f)) is approximated by

$$P(f) \simeq \frac{1}{(1 + (f\tau)^2)^{1/2}} \tag{2-1}$$

where

f = frequency

τ = carrier lifetime

For a fixed carrier lifetime, the modulation rate increases and the output power decreases. Increasing the modulation capacity of an LED requires low carrier lifetimes. This is accomplished by doping the emission region with a suitable material to decrease carrier lifetime.

Currently, light emitting diodes are commercially available which have modulation rates approaching 150 MHz without a decrease in optical power. At higher rates, manufacturers must make trade offs between high speed and optical power. Typically, high speed devices have low output powers and conversely high output light emitting diodes have low modulation frequencies. The system design engineer must be cognizant of this limitation when selecting sources for WDM systems.

Optical output of a laser diode is composed of spontaneous emission and stimulated emission. The stimulated carrier lifetime is extremely low ($<10^{-10}$ s) and modulation frequencies extending into the gigahertz range are common. However, the spontaneous carrier lifetime becomes the limiting factor in achieving these high bandwidths. This is a reason for prebiasing a laser diode at the threshold current. By modulating the laser diode in its stimulated state, the transmission data rate is not limited by spontaneous carrier lifetimes. The Air Force system requirements call for a 300 Mb/s (~150 MHz) data rate for the fastest system. Laser diodes would easily meet this requirement and light emitting diodes may be considered as sources if their operating limitations are incorporated into the system design.

A tight tolerance on the source central emitting wavelength is required to reduce optical losses and to limit crosstalk between transmission channels. The central wavelength of a semiconductor is determined from its band gap energy ($\lambda_c \sim 1.24/Eg$). Devices can be fabricated with different emission wavelengths by changing the material composition of the sources. Because the growth process of a wafer is not an exact science, fluctuations in band gap energy occur within the wafer and from wafer to wafer. Consequently, the wavelength tolerance between chips from the same wafer can be 3 nm for InGaAsP and AlGaAs devices. The central wavelength tolerance of sources from different wafer growths is typically 30 nm for AlGaAs laser diodes and approximately 100 nm for InGaAsP light emitting diodes. Some manufacturers can select from a number of laser growths to a tolerance of ±2.5 nm. Manufacturers of AlGaAs light emitting diodes typically specify the central wavelength to be within a 50 nm spectral range. For wavelength multiplexing applications, a screening process or tight specification is required to select ILD and LED sources with outputs that fall within the required wavelength interval. The degree of tolerance is dependent on the WDM system requirements.

The spectral distribution of semiconductor source emission is another critical performance factor in WDM systems. Determination, often empirical, of this parameter is required to achieve low loss and low crosstalk. Figure 2.3.1-1 is the spectral energy distribution for an InGaAsP laser diode. A standard technique in evaluating this distribution is to divide the distribution into two components - in-band radiation and out-of-band radiation. For a laser diode, the in-band radiation is defined as the stimulated emission, and the out-of-band radiation is the spontaneous emission outside the laser diode's stimulated spectral bandwidth. A laser diode has more than 90% of its total energy within the 10 dB point. The total energy is expressed by

$$P_T(\lambda) = \int_{\lambda_1}^{\lambda_2} P(\lambda)d\lambda \qquad (2\text{-}2)$$

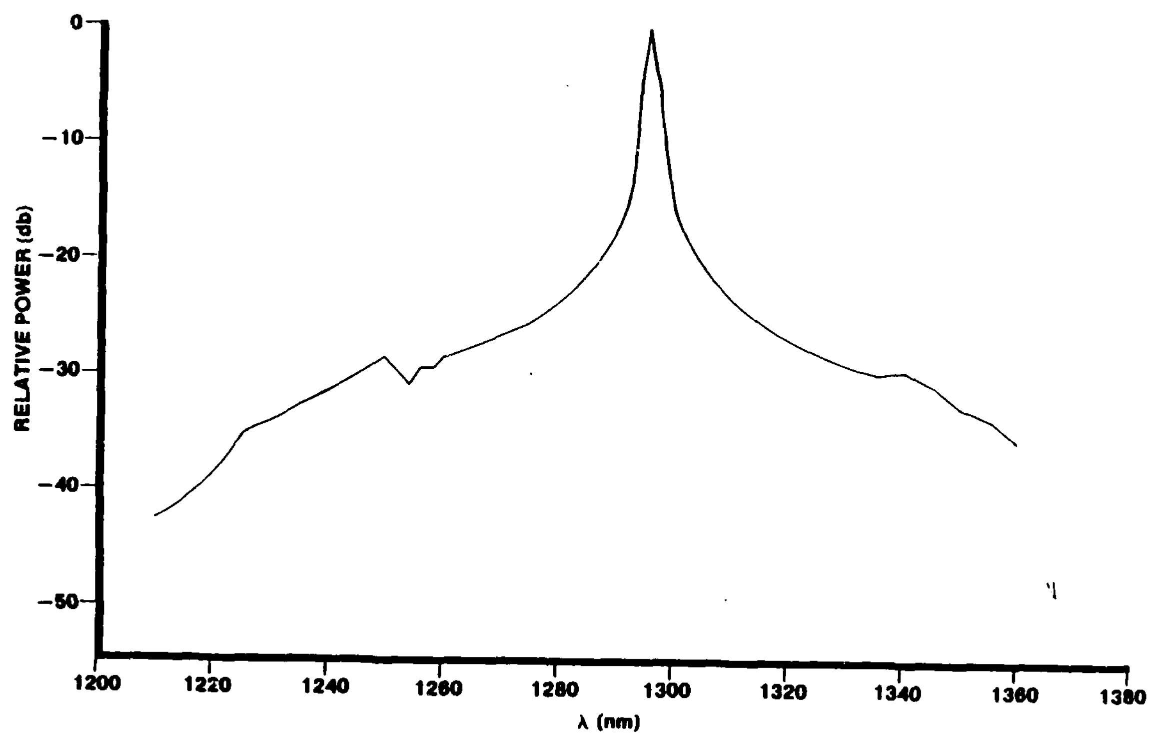


Figure 2.3.1-1. Spectral Emission of an InGaAsP Laser Diode.

23202

where

$P(\lambda)$ = laser diode (or LED) spectral distribution

λ_1 and λ_2 = source spectral limits

The above definition is not suitable when considering an LED. Figure 2.3.1-2 is the spectral energy distribution for an LED. The spontaneous emission is quite broad (~50 nm for AlGaAs devices and ~100 nm for InGaAsP devices). The definition of in-band and out-of-band energy (total energy) is expressed within particular wavelength intervals for purposes of WDM system analysis. Total emitted power, P_T, is

$$P_T = \int_{\lambda_1}^{\lambda_i} P(\lambda)d\lambda + \int_{\lambda_i}^{\lambda_f} P(\lambda)d\lambda + \int_{\lambda_f}^{\lambda_2} P(\lambda)d\lambda \tag{2-3}$$

where

$P(\lambda)$ = LED energy distribution

λ_1 = short wavelength limit

λ_2 = long wavelength limit

λ_i = initial short wavelength limit for in-band radiation

λ_f = final long wavelength limit for in-band radiation

Specific wavelength integral limits are determined by the placement of the WDM system channels. The sum of the first and third integrals is the out-of-band power (crosstalk) while the second integral is the in-band channel power.

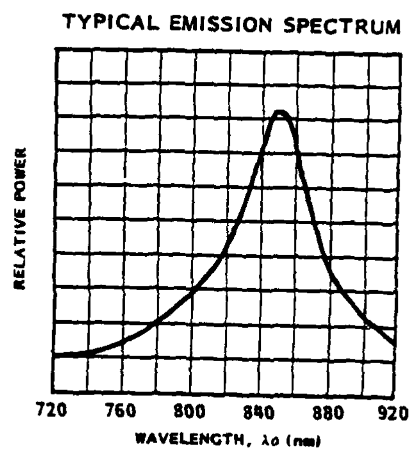


Figure 2.3.1-2. Spectral Emission of an LED.

A laser diode is a coherent emitter and its modal characteristics will affect system performance in two ways - laser modal noise and spectral width. The number of longitudinal modes will define the laser diode spectral width. A laser is classified as a multimode device when the spectral width is 3 nm to 5 nm for AlGaAs laser diodes and between 6 nm and 9 nm for InGaAsP laser diodes. As the number of modes is decreased, the width decreases. For WDM systems with many optical channels, narrow spectral widths are required. Ideally, the narrower the spectral width, the easier it is to multiplex optical channels. Figure 2.3.1-3 is an illustration of the spectral emission of a laser diode with several modes.

The wavelength spacing between adjacent modes is expressed by

$$\Delta\lambda \simeq \frac{\lambda^2}{2\bar{n}\ell} \qquad (2-4)$$

where

λ = central wavelength

$\bar{n}$ = effective refractive index of the waveguide

ℓ = cavity length

The illustrated InGaAsP laser diode has a mode spacing of approximately 1 nm. Increasing the cavity length or increasing the effective refractive index reduces the mode spacing. AlGaAs

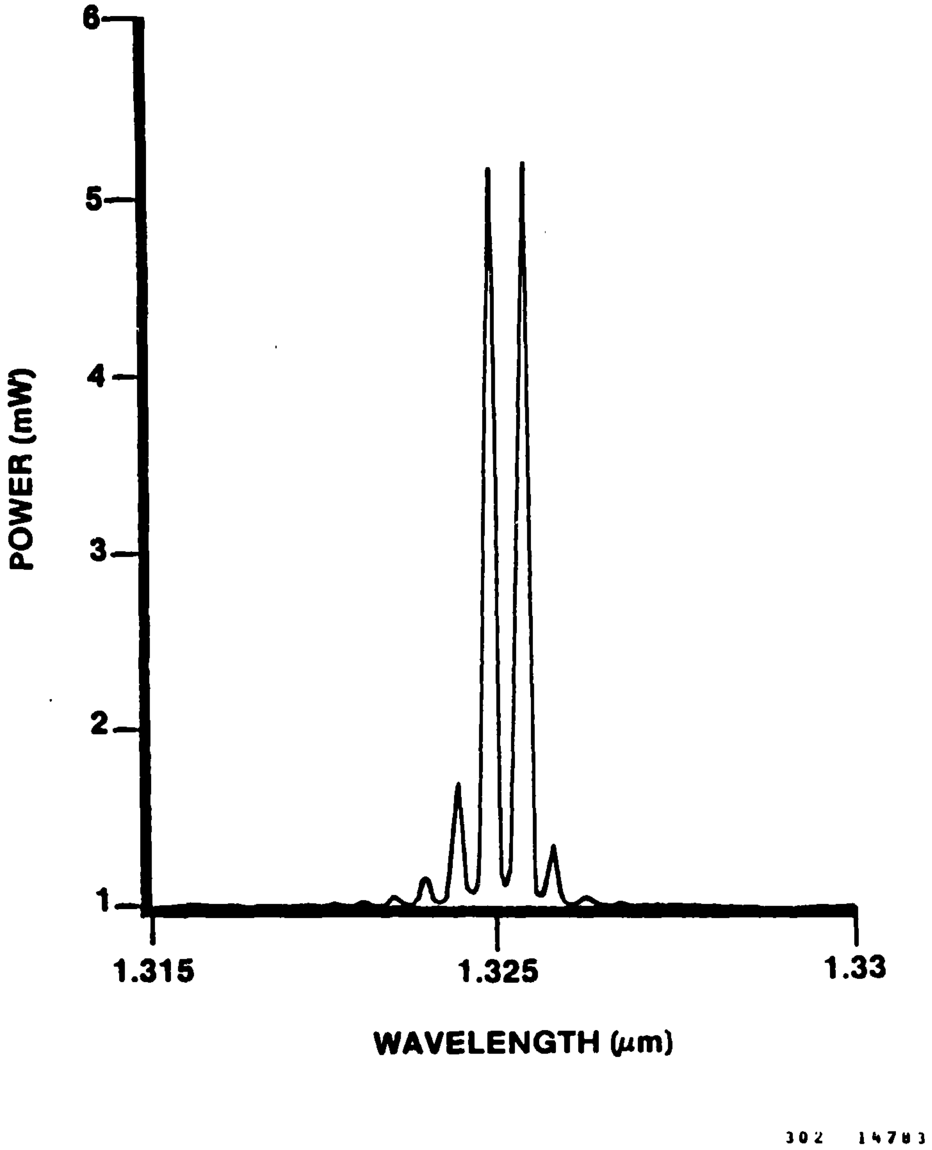


Figure 2.3.1-3. Spectral Emission of a Laser Diode Illustrating Emission From Several Modes.

multimode laser diodes have slightly smaller wavelength intervals between modes than InGaAsP laser diodes.

The total power emitted by an ILD is contained within an extremely narrow spectral region. This narrow width is beneficial for achieving increased channel separation and reduced tolerance on the central wavelength. An additional benefit is that the laser diode spontaneous emission is reduced with single-mode laser diodes. Figure 2.3.1-4 is a power versus drive current curve for an example single-mode laser diode and multimode laser diode. The level of spontaneous emission is often significantly reduced for a single-mode laser and system crosstalk is reduced.

Although there are advantages to a single-mode laser over a multimode laser, a primary disadvantage is modal noise. The coupling between a single-mode laser diode and a multimode fiber produces instabilities in the propagation of light. This noise can create an amplitude modulation of the received signal due to physical movement of the fiber, couplers, or connectors. Modal noise problems are well documented for analog fiber optic systems; however, in digital operation trade offs are possible with the digital data format (nonreturn-to-zero (nrz), Manchester, etc.) to reduce the effects of modal noise.

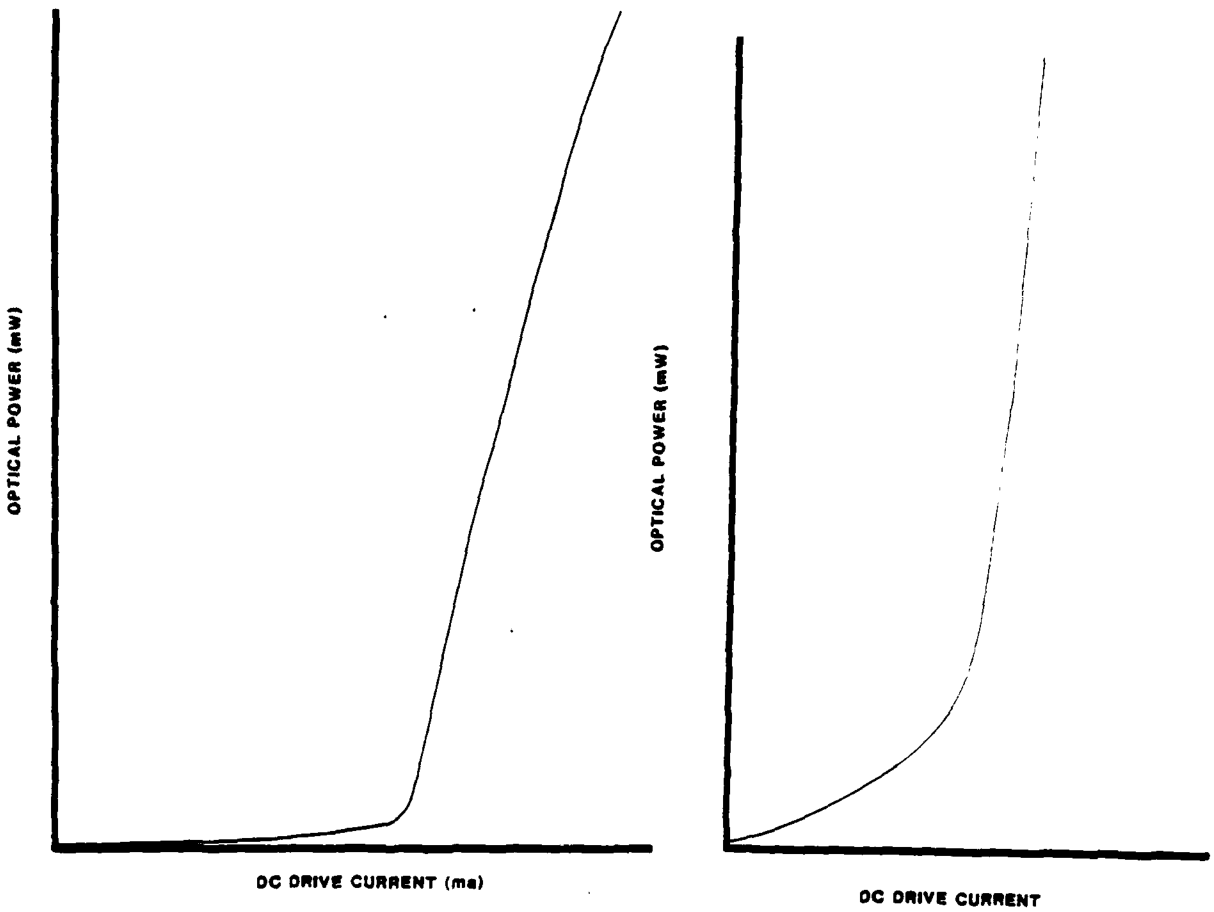


Figure 2.3.1-4. Power Emitted Versus Drive Current for Example Single-Mode and Multimode Laser Diodes. The "Soft Knee" Seen for Some Multimode Laser Diodes Is Not Always Seen.

The last source parameter to be considered affecting system performance is the coupling efficiency between the source (ILD or LED) and an optical fiber. As the source technology has advanced, the optical structure of devices (primarily laser diodes) has been changing to optimize performance, lifetime, and coupling. The primary factors affecting coupling efficiency are source spatial distribution, source geometry, and fiber numerical aperture (NA). Coupling efficiency into a fiber is determined by integrating the angular distribution of the source and is expressed by (meridional rays only):

$$CE = \frac{\int_0^{\Theta_c} I(\Theta) \sin \Theta d\Theta}{\int_0^{\pi/2} I(\Theta) \sin \Theta d\Theta} \qquad (2\text{-}5)$$

where

$I(\Theta)$ = source angular distribution

Θ_c = fiber critical angle

$\Theta_c = \sin^{-1}$ (NA)

If the source is lambertian, as is the case for a surface emitting LED, then $I(\Theta) = I_0 \cos \Theta$. The coupling efficiency is approximately equal to the square of the accepting fiber NA (assumes source diameter less than the fiber core diameter).

The coupling efficiency of a lambertian LED (surface cross section less than fiber cross section) to a fiber with an NA equal to 0.25 is approximately 6% (-12 dB). Coupling efficiency of an edge emitting LED is different from that of a lambertian source. Figure 2.3.1-5 illustrates the far-field pattern (i.e., angular distribution) for an edge emitting, double heterostructure LED. Radiation guiding perpendicular to the junction plane is due to the heterostructures and thus the emission half angle (divergence) is less than 40°. However, radiation guidance does not occur for the emission parallel to the junction plane, and the angular emission is approximately lambertian. Consequently, the emission pattern is elliptical and the coupling efficiency to an optical fiber is better than that of a surface emitting LED. An integration over the angular emission pattern and the fiber NA is required to determine the coupling efficiency.

The actual coupling process is usually accomplished with a flat butt coupling between the fiber and the source. Increased coupling efficiency can be attained by lensing the fiber end face and/or tapering the fiber.

The coupling efficiency between a laser diode and a fiber is primarily determined from the angular emission. This is due to the elimination of the area ratio mismatch between the active surface and the multimode fiber core diameter. The divergence of a laser

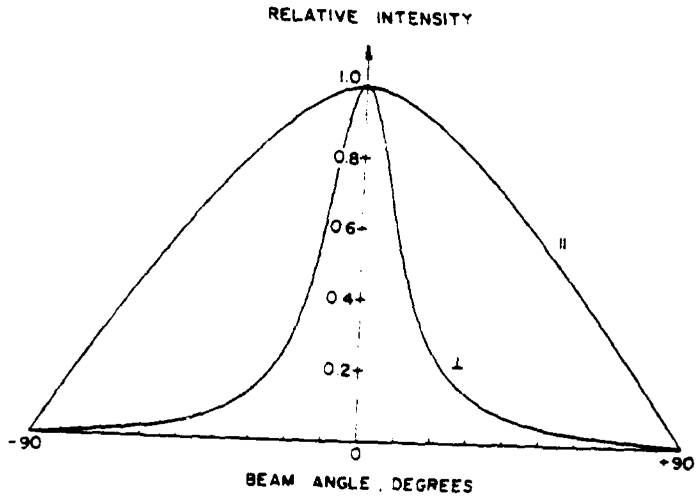


Figure 2.3.1-5. Edge Emitting LED Far-Field Angular Distribution.

23202

diode is illustrated in Figure 2.3.1-6. The divergence is inversely proportional to the active width or active thickness of the laser diode for devices with a relatively thick (>0.4 μm) active layer. This active thickness produces a beam perpendicular to the junction plane and its high emission angle (±35°) is due to diffraction. The angular emission angle (±15°) parallel to the junction plane is lower due to the increased spot size of the emission region. The coupling efficiency between a laser diode and a multimode fiber is typically greater than 50%. Special fiber preparation, i.e., lensing and/or tapering, can increase the coupling efficiency to greater than 80%.

A detailed knowledge of the preceding source parameters must be acquired prior to design and fabrication of a WDM system. Additional parameters such as temperature sensitivity, reliability, radiation resistance, etc., must and have been considered in the selection process.

2.3.2 Photodetectors

Selection of a photodiode is dependent on spectral response, bandwidth, and environmental factors. Currently, three detector compositions are used within the fiber optic transmission window. These are germanium (Ge), silicon (Si), and InGaAs(P)/InP. The Ge photodetector is unique in that its spectral response extends over

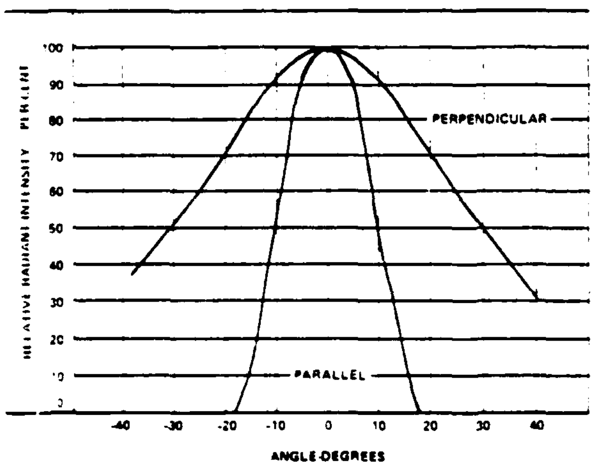


Figure 2.3.1-6. Laser Diode Far-Field Angular Distribution.

23202

the entire wavelength regime. Two types of Ge detectors are commercially available - the pin photodiode and the avalanche photodiode (APD). Both devices exhibit high noise and limited bandwidths. Additionally, Ge detectors have a response often dependent on the position of the light spot relative to the active surface. Although Ge detector technology has matured in the optics world, integration into fiber optics has not occurred. This is due to other technologies offering substantial advantages in fiber optic communications.

Silicon detectors are the most developed devices in fiber optic transmission systems. This technology has undergone substantial development so that off-the-shelf Si photodetectors are readily available to all fiber optic users. Two types of diodes are used in optical communications - pin detectors and APD detectors. These diodes are useful in the 700-nm to 1000-nm wavelength regime. Figure 2.3.2-1 illustrates the typical spectral response of a pin detector. Peak responsivity occurs near 900 nm and changes less than 10% between 700 nm and 900 nm. For wavelengths greater than 1000 nm, the spectral response decreases rapidly.

Silicon is an indirect band gap semiconductor with an absorption edge located at approximately 1150 nm. For wavelengths greater than 1150 nm, silicon does not absorb photons and electron-hole excitation does not occur (i.e., transparency). This behavior of

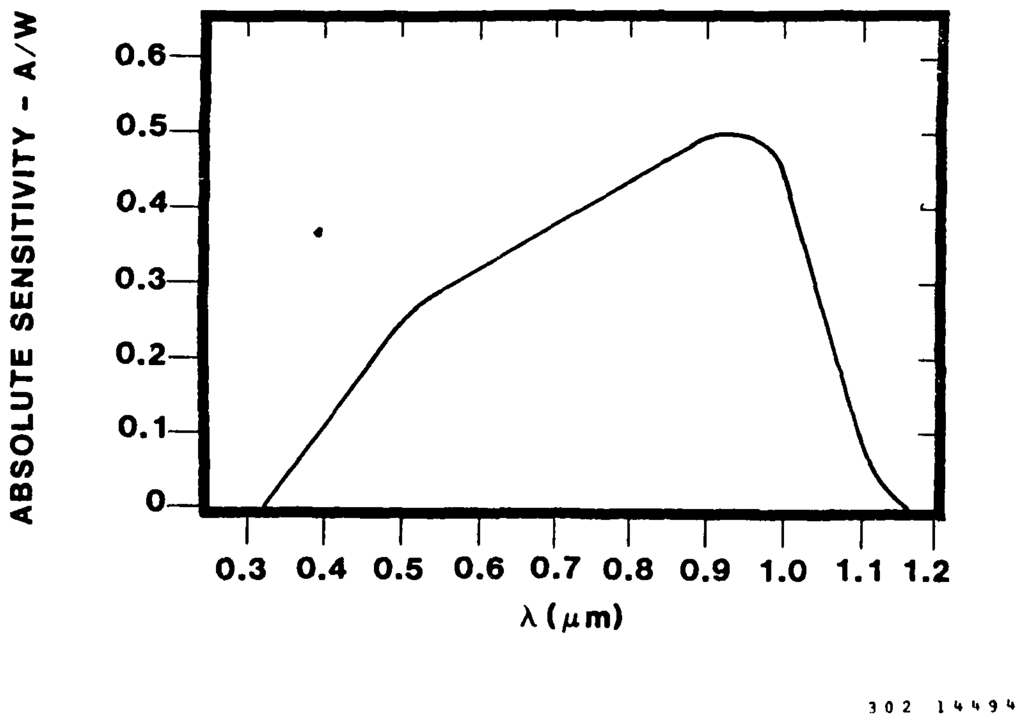


Figure 2.3.2-1. Spectral Response of a Silicon Detector.

Si can be exploited in WDM systems because channels with wavelengths >1150 nm do not interact with silicon detectors. By a proper choice of detector type, crosstalk can be reduced.

The modulation bandwidth of silicon devices (pin and APD) can be greater than hundreds of megahertz. Low noise and high bandwidth (>100 MHz pin and 200 MHz APD) receivers using silicon detectors are routinely fabricated. The advent of pin-FET combinations has yielded comparable bandwidth performance to APD diodes. Although the FET technology is in the developmental stage, enough progress has been made to predict their eventual high volume production. The pin-FET combinations have advantages over the avalanche photodiodes which require high reverse bias (hundreds of volts) and have high sensitivity to nuclear radiation.

The third detector type is the ternary or quaternary semiconductor photodiode based on InGaAsP. Their spectral response is between 1000 nm and 1600 nm for this new technology with continuing development. Presently, such pin diodes are commercially available at a significantly higher cost than silicon devices (factor of 10), but avalanche photodiodes are not readily available.

Bandwidth and spectral responsivity are the dominant optical parameters that must be known for the InGaAsP detectors. Bandwidth has been determined because it is a parameter that has become increasingly important for optical fibers with low attenuation and low dispersion within this wavelength regime. High bandwidth detectors are required to effectively use this transmission region; however, simple pin devices typically have bandwidths less than 100 MHz.

The technology for avalanche photodiodes made with InGaAsP has not advanced to a state where availability can be predicted. However, the technology for InGaAsP pin-FET detectors is undergoing rapid development and devices are beginning to appear on the commercial market. Bandwidths exceeding 200 MHz have been reported in scientific publications.

The second optical parameter of importance for the InGaAsP detectors is the spectral responsivity. By varying the material composition of quaternaries (InGaAsP), it is possible to fabricate wavelength selective detectors within the 1200 nm to 1600 nm wavelength interval. Figure 2.3.2-2 is an illustration of band gap energy as composition parameter "y" for $In_{1-x}Ga_xAs_yP_{1-y}$ nearly lattice matched to InP. Selection of suitable material constants (x,y) will yield a detector that has wavelength tunability within 1200 nm and 1600 nm. Figure 2.3.2-3 illustrates the spectral response of an InGaAsP/InP photodiode. This selectivity of a spectral response will have a significant beneficial effect on crosstalk reduction between transmission channels.

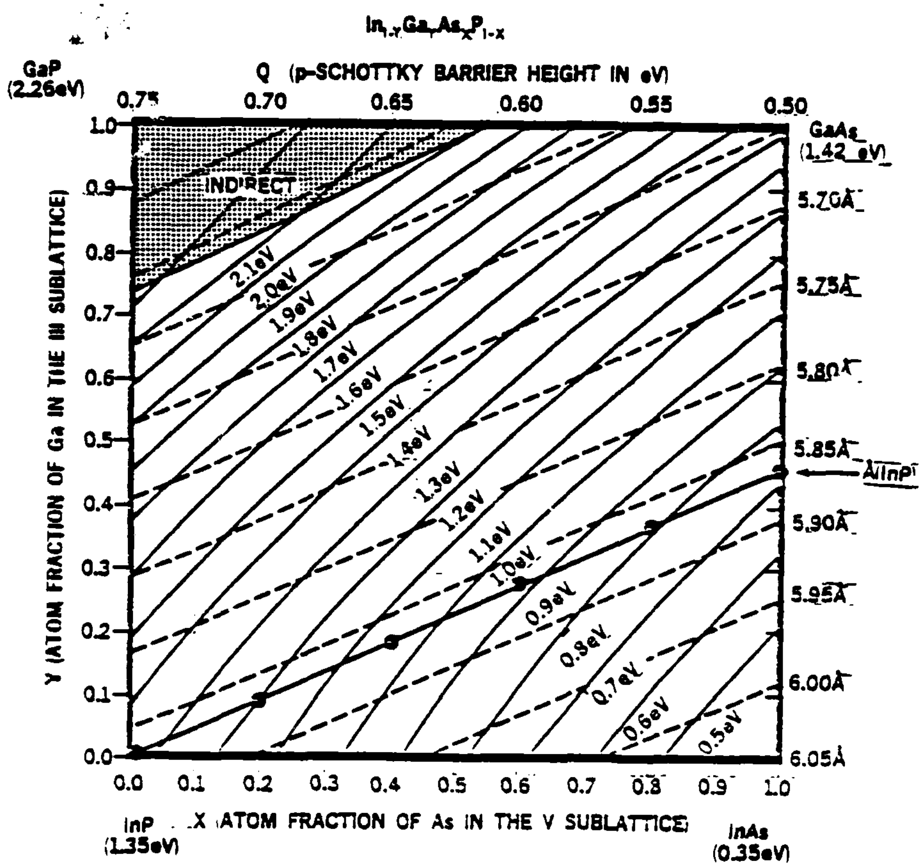


Figure 2.3.2-2. Variation of Band Gap Energy With Material Composition for InGaAsP Combinations.

23202

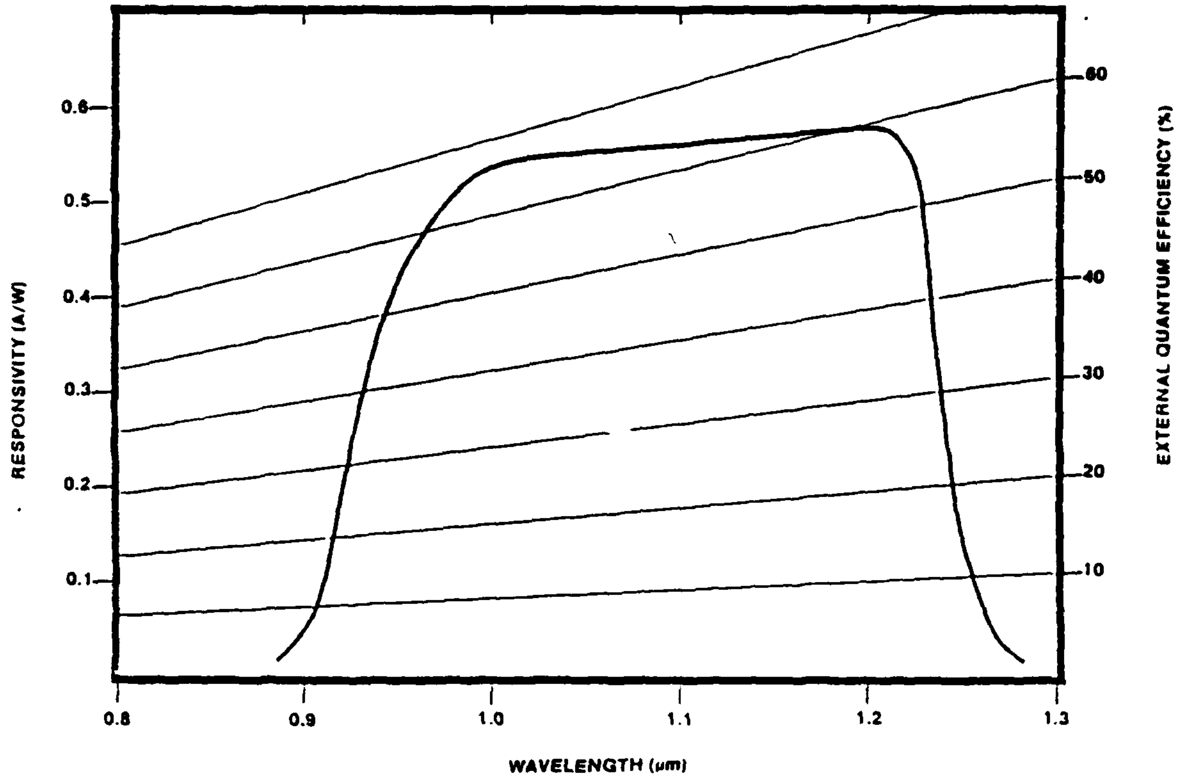


Figure 2.3.2-3. Spectral Response of an InGaAsP/InP Photodiode.

23202

A parametric analysis among detectors is a required system design effort prior to fabrication. By analyzing the detector optical characteristics, optimum system performance can be realized. Table 2.3.2-1 summarizes some of the detector characteristics covered.

2.3.3 WDM Couplers

The key optical component necessary for WDM transmission is the coupler necessary to perform the multiplexing/demultiplexing function. The chief optical parameters affecting system performance are

a. Multiplex/demultiplex coupler loss

b. Optical isolation between transmission channels (crosstalk)

Two basic coupler designs are possible - wavelength independent couplers with optical filters and wavelength dependent couplers. The former technique uses a coupler which is independent of wavelength in combination with wavelength selective filters or detectors. An obvious example of such WDM is the use of one wavelength between 800 nm and 900 nm and a second wavelength between 1200 nm and 1600 nm. The inherent spectral response of Si detectors and InGaAs(P)/InP detectors would provide the optical isolation. However, this coupler type could only be used to multiplex two channels. Additionally, the maximum theoretical coupling efficiency for either transmission channel would be 25%

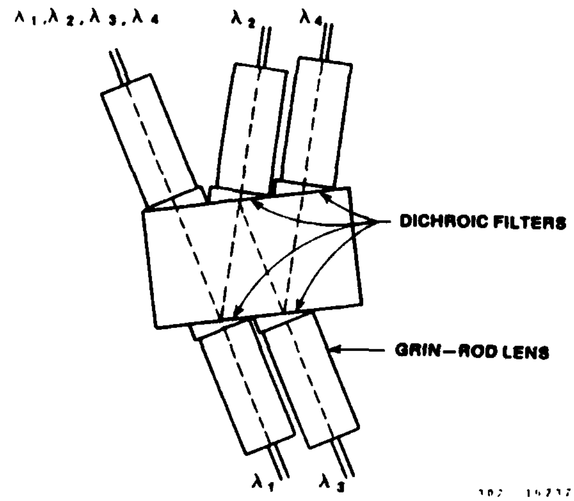
Table 2.3.2-1. Photodetectors for Consideration for WDM Systems.

Type	Advantages	Disadvantages
Germanium	• Mature technology • Avalanche photodiodes available • Wide spectral sensitivity	• High noise • Limited bandwidth compared to Si • Low APD gain
Silicon	• Mature technology • pin and APD available • Low cost • pin-FET technique useful	• Transparent to wavelengths $\gtrsim$1100 nm
InGaAsP	• Responsive from ~1000 nm to 1600 nm • InP capping layer can be used to reduce crosstalk • Spectral response can be adjusted by composition change • pin-FET technique useful	• Developing technology • APD not readily available • High cost • Unknown reliability

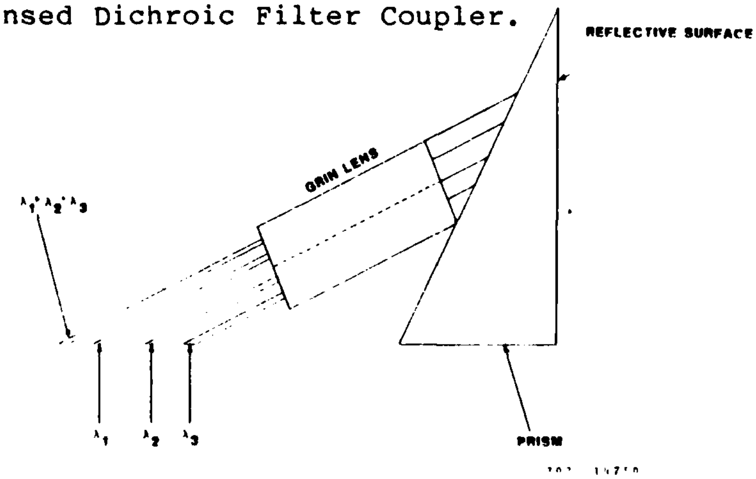
(3 dB coupling loss for each coupler). This technique is not suitable for the majority of WDM systems and, therefore, wavelength independent couplers with filters or selective detectors can be eliminated from consideration.

The wavelength dependent coupler technique is the preferred approach in achieving optimum WDM system performance. Two techniques are available to provide the selectivity: wavelength dependent interference filters (dichroics) and angularly dispersive elements (prisms and diffraction gratings). Figure 2.3.3-1 illustrates the coupler designs. The dichroic filter coupler utilizes interference filters to multiplex/demultiplex the optical signals. The coupler functions through the collimation and refocusing of optical beams through lenses and wavelength selective dichroic filters which transmit or reflect specific wavelengths. These couplers offer good coupling efficiency and good optical isolation between transmission channels. They are stable devices which do not require an extremely high tolerance on the source central wavelength. This would have a significant cost impact when compared to coupling devices requiring a high tolerance on source stability.

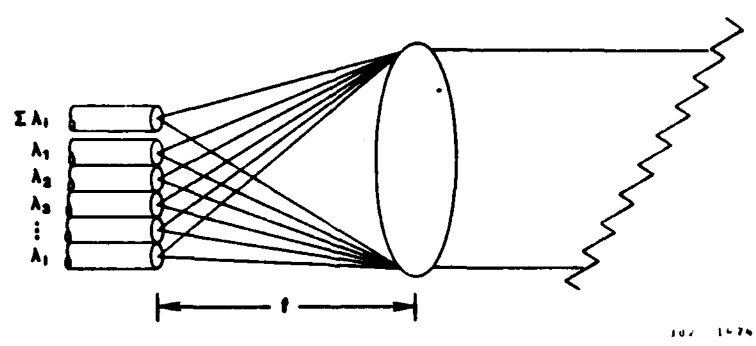
The second coupler configuration is the prism device. This coupling technique uses the dispersive properties of a prism to perform the multiplexing/demultiplexing functions. The dispersive



a. Lensed Dichroic Filter Coupler.



b. Prism Coupler.



c. Diffraction Grating Coupler.

Figure 2.3.3-1. Wavelength Division Multiplexing Coupler Designs.

properties of a prism are nonlinear with respect to wavelength, and this is the primary reason that the prism coupler is not considered a superior technique for multiplexing/demultiplexing optical channels.

A highly publicized design for an angular dispersive WDM coupler is the diffraction grating coupler. The diffraction grating coupler uses diffraction of light to perform the multiplexing/demultiplexing of the optical channels. This type of coupler is mandatory when WDM transmission of many channels (approximately eight) is required. The optical coupling efficiency and optical isolation between channels is dependent on the coupler and the optical characteristics of the sources (laser diodes or light emitting diodes). Although both types of sources could be used in a grating coupler, optimum performance is achieved with laser diodes (due to their narrow spectral widths).

Of the three types of wavelength selective couplers, the dichroic filter and diffraction grating couplers are preferred for multiplexing/demultiplexing optical channels. Each technique has advantages and disadvantages. The specific system operating requirements will dictate which type of coupler is required. Table 2.3.3-1 lists the coupler types and their known advantages and disadvantages. Each of the possible coupler types discussed in this section has been fabricated at at least several

Table 2.3.3-1. Wavelength Division Multiplexing Coupler Types.

Coupler Type	Advantages	Disadvantages
Wavelength independent with selective filters or detectors	• Simple • Low cost	• High loss • Limited to a few channels
Dichroic filter	• Simple • Low cost • Demonstrated temperature stable • 10 channels demonstrated	• Loss increases with number of channels • High initial cost for filters
Prism	• Loss not a function of number of channels • Many channels possible	• Nonlinear dispersion • Large size or exotic prism materials required • Tight source specs
Grating	• Loss not a function of number of channels • Many channels possible • Many good results published	• Tight source specs • Unknown stability

organizations and successful optical performance has been reported. Little data exists, however, on environmental stability, reliability, and cost.

2.3.4 Recommended Component Development

Major improvements are possible in the design of WDM avionics systems for the 1983-1985 time frame if some critical component development work is done. This possible work, outlined in Table 2.3.4-1, is in the areas of sources, detectors, and couplers. The arguments for the choices made in Table 2.3.4-1 stem largely from basic avionics systems requirements.

Replacement of lasers and avalanche photodiodes with light emitting diodes and pin-field effect transistors would improve system performance. The current reasons for using lasers and avalanche photodiodes are (a) the existence of high optical losses and (b) the need for high system speed. The pin-FET receivers, with sensitivity and speed approaching that of APD receivers, could be used in LED powered systems. High speed light emitting diodes (>200 MHz) could eliminate the need for lasers in all but the most demanding links. It is well known that lasers and avalanche photodiodes using fiber optic circuits are less reliable and more expensive than circuits using light emitting diodes and pins. Development of avionics light emitting diodes and pins

Table 2.3.4-1. Recommended Avionics WDM Component Developments.

Component	Rationale
High speed light emitting diodes	Eliminate or reduce need for lasers
pin-FET receivers	Eliminate need for APD photodetectors
Wavelength stable lasers	Allow closer WDM channel spacing
WDM couplers with many channels (>8)	Provide more capacity per fiber
Optical connectors and fibers	Reduce insertion loss and variations in insertion loss of connections

(including pin-field effect transistors) would greatly advance the time frame for actual use of avionics WDM fiber optic systems.

to make the most of the available information transfer capacity of avionics fiber optic links, WDM couplers should be developed with more channels and higher selectivity. These couplers, which would most likely use diffraction gratings, would be the basic multiplexing elements in very large systems. As the sensitivity analysis work of this report shows, such selective couplers would enable LED sources to be used in systems where lasers are now considered necessary.

WDM avionics systems share a common need with non-WDM systems for low loss and low variation in connectors. It is necessary in aircraft construction to provide cable connectors between major airframe subassemblies as well as at the avionics modules being connected. Currently available connectors seriously compromise system designs which use a large number (>4) of connectors in series. This problem is evident in Section 3.0 of this report where base line designs for the Air Force specified systems are developed. For each connector in a link, ITT EOPD shows that a loss of 1.2 ±0.5 dB is incurred. A link with six connectors suffers a loss of 7.2 ±3.0 dB for the connectors alone. It should be possible, by connector development and by cable specification, to reduce these losses and to ease the system design problems they cause.

3.0 AIR FORCE BASE LINE SYSTEM DESIGNS

The detailed designs produced for three Air Force specified systems are presented in this section along with the technical rationale to support the designs. Some of this rationale is derived from the Technology Forecast, Section 2.0. It must be remembered, when considering these designs, that technology to build the systems at low risk must be available in the 1983-1985 time frame. This study has attempted to gage the pace of development of the critical items (sources, detectors, and couplers) and is designed for the 1983-1985 time frame. The study makes clear the importance of tightly specified laser diodes, pin-field effect transistor (FET) detector-amplifiers, and WDM couplers. Stimulation of development in each of these areas is needed.

The specifications for the three Air Force systems defined in the SOW (attached as Appendix A) are contained in Table 3.0-1. Reference to these specifications should be made during consideration of the base line designs.

3.1 Air Force System I - Synchronous Bidirectional Link

The base line design for system I is illustrated in Figure 3.1-1. Simultaneous transmission of clock and data in both directions is achieved through the use of two nearly identical lensed dichroic couplers (see paragraph 2.3.3). The couplers are not exactly

Table 3.0-1. Air Force System Specifications.

SYSTEM I

Air Force selected parameters (system I)

Multichannel, point-to-point link

Duplex

Protocol: one to n emitters transmitting at any one time

Digital data rate (DR): DR >100 Mb/s per channel

Number of wavelengths (n): n >4

SYSTEM II

Air Force selected parameters (system II)

Multichannel, point-to-point link

Simplex (undirectional)

Protocol: one to n emitters transmitting at any one time

Digital data rate (DR): DR >300 Mb/s per channel

Number of wavelengths (n): n >8

Table 3.0-1. Air Force System Specifications (continued).

SYSTEM III

Air Force selected parameters (system III)

Multiterminal data bus

Protocol: one to n emitters transmitting at any one time

Number of terminals (m): $3 < m < 32$

Number of wavelengths (n): $2 < n < 8$

Digital data rate (DR): 1 Mb/s $< DR < 20$ Mb/s per channel

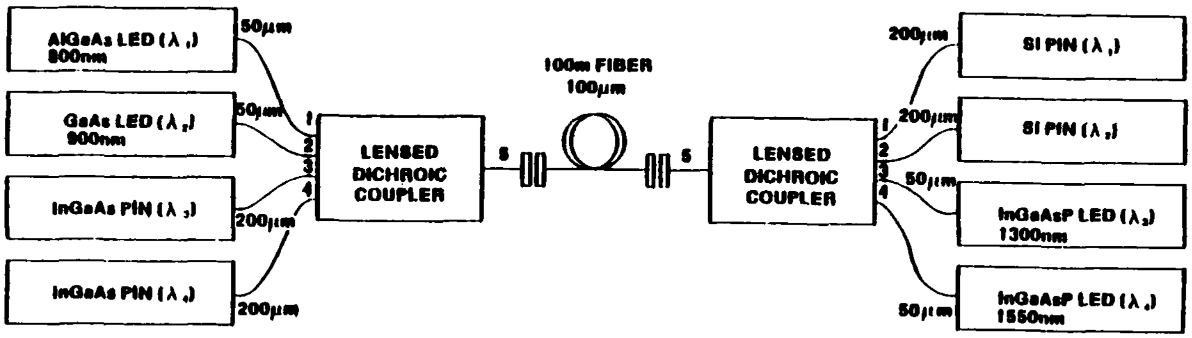


Figure 3.1-1. System I - Synchronous Bidirectional Link.

23202

identical because fibers of increasingly larger core diameters are used as paths to propagate the desired signal over the link. That is, 50-μm core fibers are used to couple LED sources to the lensed dichroic couplers; a 100-μm core fiber is used for the transmission fiber and 200-μm core fibers are used at detectors. This technique is predicted to give 1.5 ±0.5 dB loss in all the desired signal paths of the lensed dichroic couplers.

Since system I has a minimum requirement of 100 Mb/s data rate, it is possible to use LED sources and pin photodiode detectors. In this study, light emitting diodes will be selected over lasers whenever possible because of their reduced cost and more desirable environmental characteristics. Similarly, pin photodiodes will be selected over avalanche photodiodes because the latter are far less desirable for avionics applications, e.g., cost requirements for a temperature compensated high voltage bias and susceptibility to nuclear radiation when that becomes a consideration. For the initial analysis, a restricted data code which guarantees occasional transitions within the data and requires a channel bandwidth of approximately one-half the data rate will be assumed. Such schemes include scrambled nonreturn-to-zero (nrz), delay modulation code, and bit insertion.

An analysis of the performance of system I is summarized in Table 3.1-1. This analysis represents the performance expected from

Table 3.1-1. System I - Synchronous Bidirectional Link Performance Analysis.

Item	Loss
Two lensed dichroic couplers (1.5 ±0.5 dB)	3.0 ±1.0 dB
Two connectors (1.2 ±0.5 dB)	2.4 ±1.0 dB
100-m fiber (at 4.0 dB/km)	0.4 dB
Total path loss	5.8 ±2.0 dB
Source coupled power	-13.0 ±0.5 dBm
Detector coupled power	-18.8 ±2.5 dBm
Receiver sensitivity (100 Mb/s nrz)	-29.0 dBm
Link performance margin	10.2 ±2.5 dB

undegraded components. Temperature effects will be considered in the sensitivity analysis. The design rationale flow chart used for system I is shown in Table 3.1-2.

3.2 System II - Eight Channel Unidirectional Link

The base line design for system II is illustrated in Figure 3.2-1. Simultaneous transmission of data over eight separate channels in the same direction is achieved with two nine-port diffraction grating couplers. As in system I, increasingly larger fibers (as signals propagate through desired signal paths) are used to minimize coupler throughput loss. The desired path loss of 1.5 ±0.5 dB is also predicted for the diffraction grating couplers used in system II.

Since system II has a minimum data rate requirement of 300 Mb/s, semiconductor injection laser diode sources must be used because LED devices presently do not provide adequate speed. Use of a restricted data code is also assumed for system II; that is, a channel bandwidth of approximately 150 MHz is required.

All lasers used in system II are AlGaAs with equally spaced (12.5 nm spacing) wavelengths over the range of 760 nm to 847.5 nm. The technology to develop these lasers is predicted to be available within the near future as a result of development for the optical disc recorder markets. Silicon pin photodiodes are

Table 3.1-2. Design Rationale Flow Chart for System I.

Specification	Design Decision
Duplex (over one fiber)	Use 800-900 nm region for one direction and 1200-1600 nm region for other direction to reduce near-end crosstalk
Number of wavelengths >4	Use lensed dichroic couplers for simplicity, reliability, and low cost; consider grating couplers only if number of wavelengths $\gtrsim 8$
Data rate >100 Mb/s per channel	Sources can be light emitting diodes if number of wavelengths $\lesssim 6$
Wavelengths	Separate by >100 nm to reduce far-end crosstalk

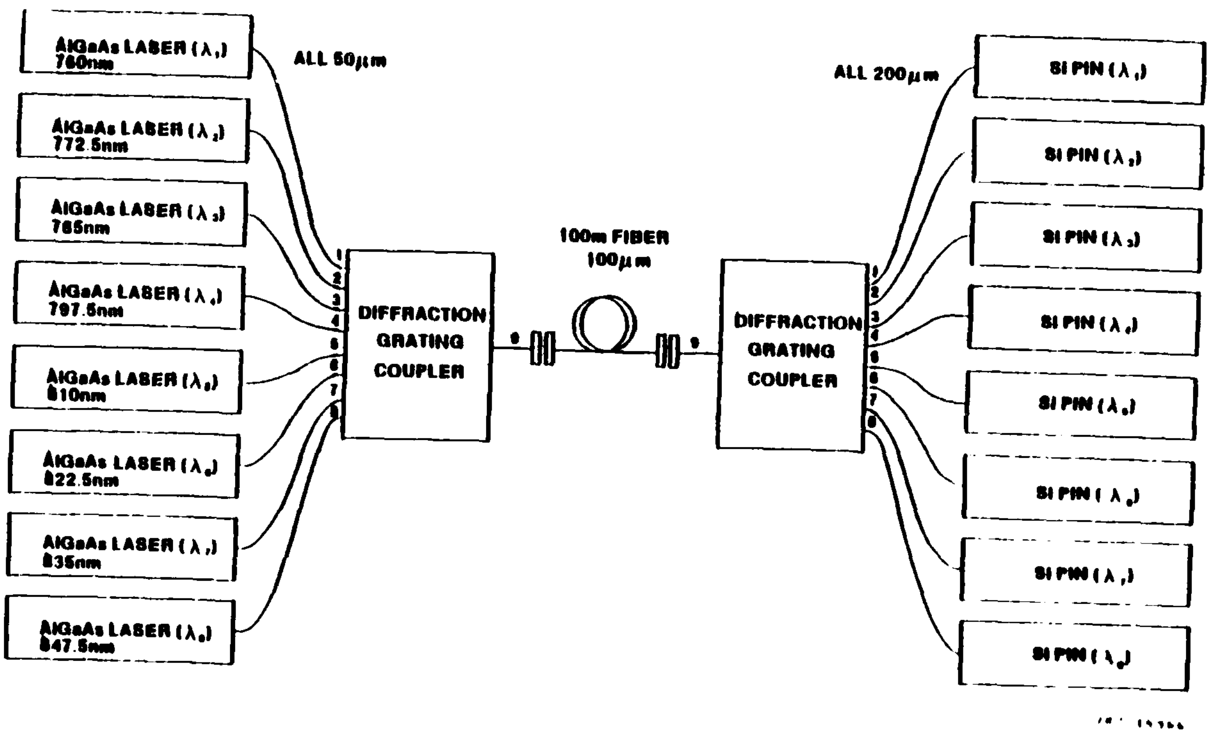


Figure 3.2-1. System II - Eight-Channel Unidirectional Link.

used for all detectors. System II performance is summarized in Table 3.2-1 and the design rationale flow chart is given in Table 3.2-2.

3.3 System III - Data Bus

The base line data bus for system III was selected based on first-hand experience at ITT EOPD with the development of electronics for high speed, bursty, asynchronous data buses. Such electronics is costly; consumes a considerable amount of space, weight, and power; requires encoding to embed the clock in the data; and at high data rates requires a preamble and synchronization pattern to acquire clock and synchronize the data. By WDM, clock can be transmitted along with the data from any of 32 terminals at any given time. Terminal transmissions in this base line are still time division multiplexed in a manner suitable to meet the needs of the particular application. Figure 3.3-1 illustrates the design; each terminal has two lensed dichroic couplers. As in systems I and II, these couplers are identical except for the different fiber core sizes used to minimize loss in the system.

All terminals are interconnected via a centralized 32-input/ 32-output transmissive star coupler. Therefore, each data bus terminal is connected to the star coupler via two fibers; one is dedicated to transmitting clock and data from the terminal to the star and the other is dedicated to transmitting clock and data from the star coupler to the terminal.

Table 3.2-1. System II - Eight-Channel Unidirectional Link Performance Analysis.

Item	Loss
Two diffraction grating couplers (1.5 ±0.5 dB)	3.0 ±1.0 dB
Two connectors (1.2 ±0.5 dB)	2.4 ±1.0 dB
100-m fiber (at 4.0 dB/km)	0.4 dB
Total path loss	5.8 ±2.0 dB
Source coupled power	-6.0 dBm
Detector coupled power	-11.8 ±2.0 dBm
Receiver sensitivity (300 Mb/s nrz)	-24.5 dBm
Link performance margin	12.7 ±2.0 dB

Table 3.2-2. Design Rationale Flow Chart for System II.

Specification	Design Decision
Data rate >300 Mb/s per channel	Sources must be laser diodes to meet this speed
Simplex (unidirectional)	All channels may be in one window because near-end crosstalk does not exist
Number of wavelengths >8	Use diffraction grating coupler to achieve low loss; use laser diodes for close channel spacing
Wavelengths	760 nm to 847.5 nm with 12.5 nm spacing to make use of available proven AlGaAs sources and Si detectors

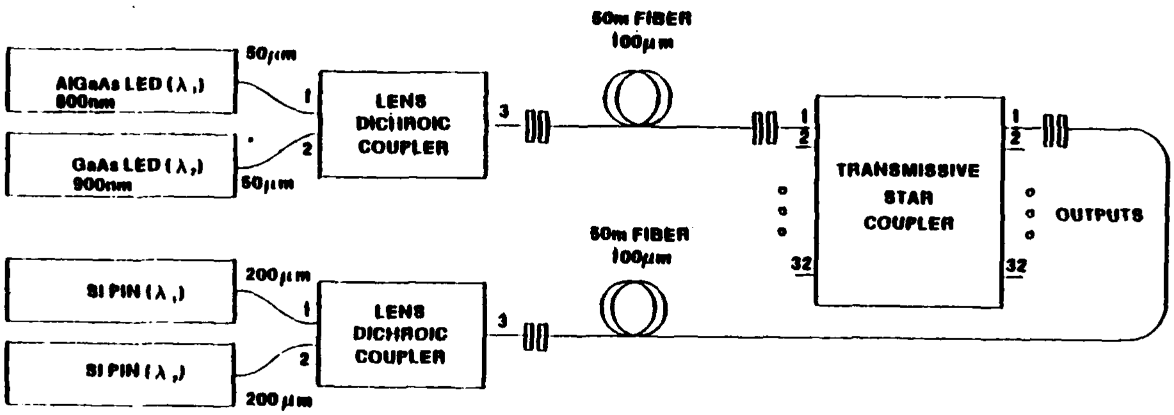


Figure 3.3-1. System III - Data Bus.

Experience at ITT EOPD has shown that a 32 x 32 transmissive star coupler attenuates the optical signal power entering any one of its input ports by 16.5 ±1.5 dB at any of the output ports. This represents an excess beyond the theoretical power dividing loss of 15 dB. The lensed dichroic couplers are predicted to introduce 1.5 ±0.5 dB of loss in any of the desired signal path combinations.

Again as in systems I and II, a restricted data code which ensures some transitions in the data and which halves the bandwidth requirement can be used. Since clock is transmitted along with the data, there is no need to use Manchester encoding. The minimum data rate for system III of 20 Mb/s requires approximately 10 MHz bandwidth for scrambled nrz. Table 3.3-1 shows the design rationale for system III.

An analysis of the performance of system III is summarized in Table 3.3-2. The analysis indicates an undegraded 8.3 ±5.5 dB performance margin. This is not large enough for practical systems. Options are to decrease the number of terminals, increase the source coupled power, or increase the receiver sensitivity. The simplest solution is to decrease the number of terminals; however, this may not be a viable option for some applications. Increasing the optical power can be achieved by selecting higher power light emitting diodes or using laser diodes. Use of a laser

Table 3.3-1. Design Rationale for System III.

Specification	Design Decision
Number of terminals, m, from 3 to 32	Design for upper specification of 32 terminals using star coupler
Number of wavelengths, n, from 2 to 8	Initial design for two channels, expand if link budget allows
Digital data rate from 1 Mb/s to 20 Mb/s per channel	Use LED sources for reliability, availability, and low cost
Star coupler	32 x 32 port transmission star coupler for isolation of transmited and received power
Wavelengths	800 nm and 900 nm to achieve maximum separation and reduce far end crosstalk

Table 3.3-2. System III - Data Bus Performance Analysis.

Item	Loss
One 32 x 32 transmissive star coupler	16.5 ±1.5 dB
Two lensed dichroic couplers (1.5 ±0.5 dB)	3.0 ±1.0 dB
Four connectors (1.2 ±0.5 dB)	4.8 ±2.0 dB
100-m fiber (at 4.0 dB/km)	0.4 dB
Total path loss	24.7 ±4.5 dB
Source coupled power	-10.0 ±1.0 dBm
Detector coupled power	-34.7 ±5.5 dBm
Receiver sensitivity (20 Mb/s nrz)	-43.0 dBm
Bus performance margin	8.3 ±5.5 dB

is not a simple solution because of the difficulty of stabilizing the output power with nonrestricted and bursty data. Increasing source coupled power may be a viable option.

Receiver sensitivities thus far have been extrapolated from receiver performance data for bipolar transimpedance preamplifiers. Recently much attention has been given to the pin-FET integrating preamplifer. D. R. Smith and R. C. Hooper of the British Post Office Research Center have reported in a number of published papers their results with a pin-FET hybrid optical receiver. They have shown how receiver sensitivities comparable to conventional APD-based receivers can be achieved with a low-capacitance, low-leakage current pin photodiode and an FET high-impedance front-end preamplifier. The design provides both cost and operational advantages over APD receivers. Low voltage operation, stability over temperature, higher saturation levels, and absence of microplasma noise mechanisms are among the more significant technical advantages. Smith and Hooper have demonstrated a 10^{-9} error rate for -46.0 dBm received average signal power at 140 Mb/s nrz and 0.85 μm wavelength. This is only 4.0 dB worse than a conventional silicon APD receiver. At 1.24 μm, a GaInAs pin photodiode was shown to achieve a -41.0 dBm sensitivity which, with the absence of microplasma noise (a problem with long wavelength avalanche photodiodes), is equal to or better than presently possible with APD technology.

The pin-FET approach reported by Smith and Hooper has been adapted by Plessey Optoelectronics and Microwave Ltd. and is currently being marketed as a hybrid module (the CXL M1) optimized for use at 1300 nm. This specified sensitivity at 140 Mb/s nrz is -37 dBm (approximately 4.0 higher than Smith and Hooper reported).

The utility of the pin-FET integrating preamplifier for data bus applications is questionable at present because of the poor low frequency response of the technique. However, if the technique can be adapted for use in data buses, a considerable performance advantage is gained. A sensitivity of -46.0 dBm at 140 Mb/s nrz extrapolates to approximately -55.0 dBm at 20 Mb/s nrz. Applied to system III, this gives a performance margin of 19.7 ±4.5 dB above the sensitivity level.

4.0 SYSTEM SENSITIVITY ANALYSIS

The performance of the three Air Force base line system designs presented in the previous report sections was investigated using sensitivity analysis techniques. These techniques provide a means of quantifying the relationship between a change in system parameters and the effect of the change on system performance. Through these system sensitivity analyses, the performance of WDM fiber optic components in the three Air Force systems was studied. In two of the systems, the analysis led to needed component improvements. In all of the systems, the analysis yielded an insight into component operations and a confidence in overall system integrity.

The system sensitivity analysis was carried out by using a set of computer programs known at ITT Electro-Optical Products Division (EOPD) as the Optical Circuit Analysis Program (OCAP). OCAP, as diagramed in Figure 4.0-1, is composed of a data base segment, developed prior to this contract at ITT EOPD, and three system algorithm segments. The program segments developed under the contract are specific analysis routines for Air Force systems I, II, and III. Appendix C contains the FORTRAN code of these OCAP segments and detailed information on the organization of component data. This appendix also contains example computer run printouts.

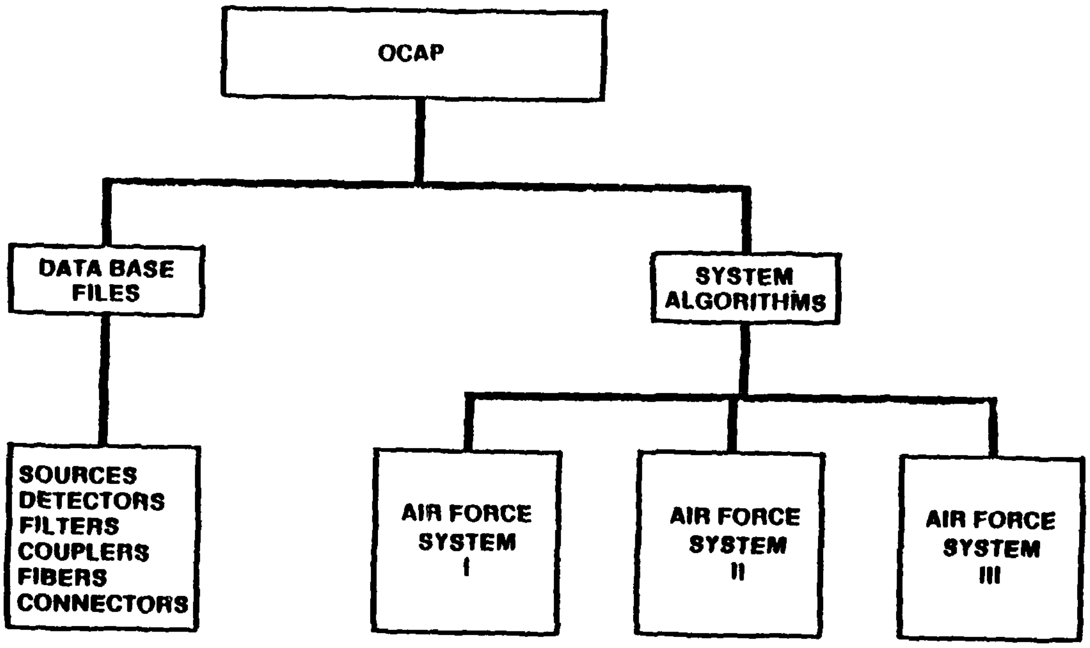


Figure 4.G-1. Optical Circuit Analysis Program (OCAP) Architecture.

23202

The data base includes the sources, detectors, filters, couplers, and fibers necessary for operation of the three Air Force systems. Devices in the data base are referenced by nine-digit key numbers. The first digit indicates the type of component, the second four digits uniquely define the component, and the last four digits indicate the port-to-port path for couplers. The data base has the capacity to store type, part number, manufacturer, description, source of information, and measurement conditions for each device. This additional information greatly enhances the capabilities of the program for use in designing a system with optimum response.

The data base is accessed through device subroutines. These subroutines retrieve the data and then interpolate the data to recreate the spectral curve of the device. Accuracy of the data was assured by using a test interpolation program identical to that used by the subroutines. The data was interpolated and plotted showing the interpolated data and a straight line approximation of the input data points. Figure 4.0-2 illustrates the accuracy achieved for a typical component. Accurate fits for most components were achieved using data points spaced every 5 nm. Components with rapidly varying spectral response required data points spaced every 1 nm. No effort was made to fit the fine structure of laser diode emission spectra because it has little effect on the relatively widely spaced WDM channels considered for avionics uses.

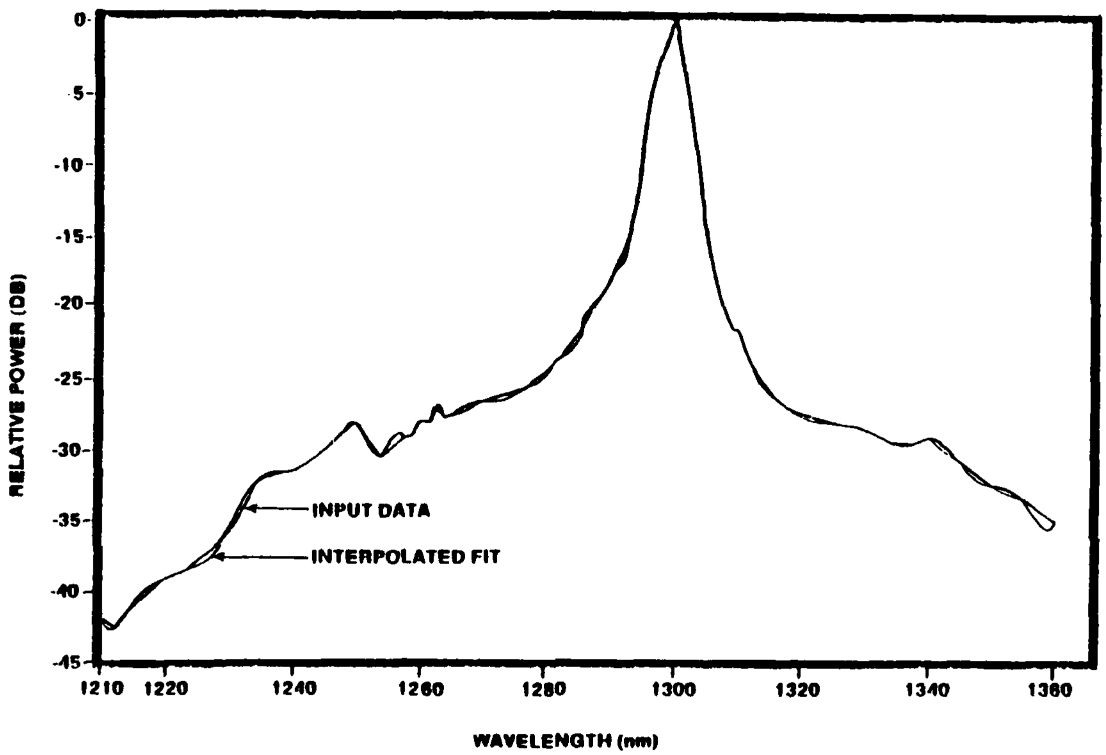


Figure 4.0-2. System II, Source 4 - Relative Power Versus Wavelength.

The main OCAP program (see the flow chart in Figure 4.0-3) calls for subroutines which initialize constants and variables of the system. The device subroutines are then called in the order specified by an input file. The input file indicates the structure of the system to be analyzed. After the data is received via the device subroutine, the integrating subroutine is called. The integrating subroutine calculates the power in the link after each component as a function of wavelength. When the source to detector path is completed, the total loss of power over the path is calculated in dB relative to the input power. Upon completion of all the paths specified by the input file, the output is printed in matrix form showing the loss in power for each source at each detector as the sources are "turned on" one at a time. The matrix also lists the total crosstalk at each detector when all the sources are "on" simultaneously. The input file provides sensitivity analysis capabilities by allowing changes in loss and wavelength for all components. All three system algorithms ran with excellent results. The modeled system responses behaved as real systems would have been expected to behave.

4.1 Initial OCAP Use

The initial use of the OCAP program was to confirm the performance estimated for the three Air Force systems designed during the base line systems design activity discussed in Section 3.0 of this report. OCAP was later used in a more detailed sensitivity

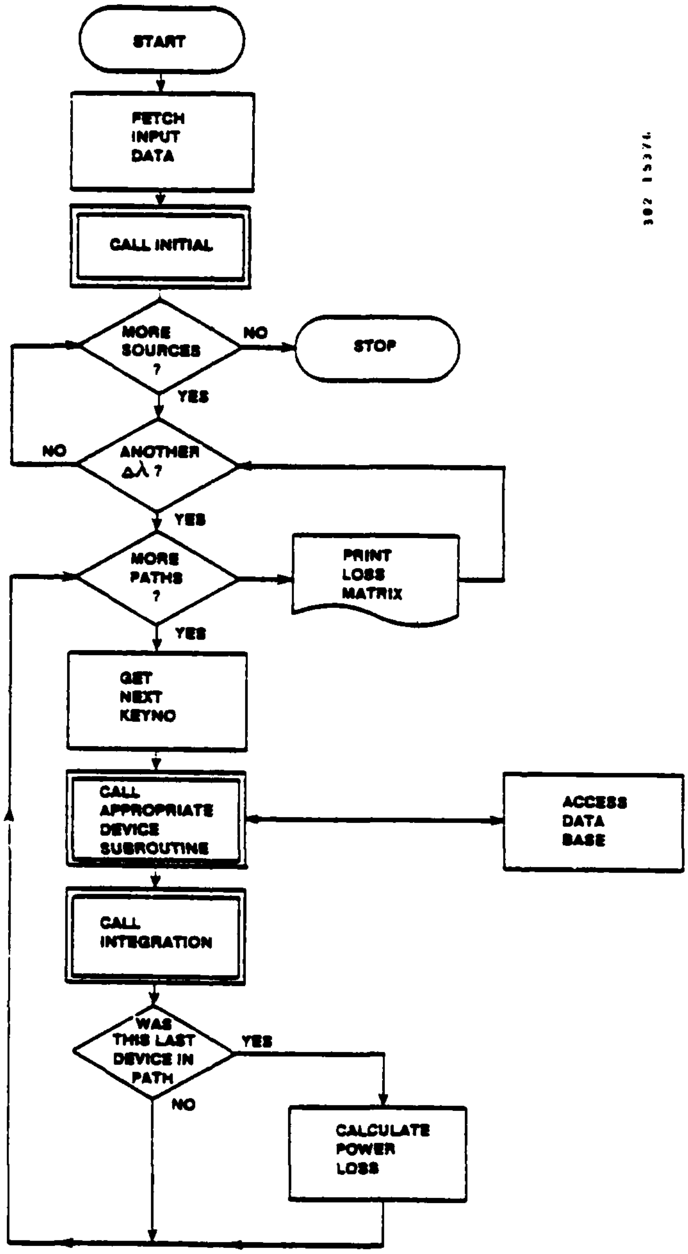


Figure 4.0-3. Main Program - General Flow Chart.

23202

analysis of the systems. These detailed analyses are reported in paragraph 4.3 of this report.

System I initial analysis results, printed in Table 4.1-1, show the usefulness of the program as a design aid. A first run of the program showed more crosstalk than desired on two channels. A spectral plot, produced by the computer program at operator request, showed that the crosstalk was a result of poor coupler performance. Adding additional filters to the two offending channels improved the performance to an acceptable level. Near-end crosstalk was found to be very low; power detected was approximately 60 dB down from the input power. Far-end crosstalk, involving channels closer in wavelength, showed detected power to be about 35 dB below input power or about 23 dB below in-band received power.

System II used a diffraction grating coupler and the sensitivity analysis results showed this coupler to be a highly selective device. Power at throughput (in-band) detectors was 13 dB down relative to input power but power at out-of-band detectors was 46 dB down. In a system with such closely spaced (12.5 nm) channels, it is expected that the system will be very sensitive to changes in source wavelength. Sensitivity analysis showed this to be true. Drifts in optical source wavelength of 10 nm increased channel loss from 14 dB to 33 dB. The crosstalk into other

Table 4.1-1. System I Initial Analysis Results: Path Insertion Loss in dB.

a. Before Adding Filters

Sources	Detectors 1	2	3	4
1	10.26	11.18	55.88	55.88
2	33.30	11.55	51.51	51.51
3	62.97	62.97	12.53	13.46
4	62.92	62.92	35.91	14.70
Total Crosstalk	-33.29	-11.18	-35.75	-13.45

NOTE: Crosstalk from Source 1 to Detector 2 and from Source 3 to Detector 4

b. After Adding Filters

Sources	Detectors 1	2	3	4
1	10.26	34.10	55.88	64.09
2	33.30	12.45	51.51	64.00
3	62.97	65.96	12.53	36.45
4	62.92	65.91	35.91	15.13
Total Crosstalk	-33.29	-34.09	-35.75	-36.44

channels from the changing source, however, did not change dramatically due to the high selectivity of the multiplex coupler. The change in total crosstalk was only about 2 dB. Figure 4.1-1 illustrates the sensitivity of system II to the change in emission wavelength of source 4. It is evident that drifts of more than 2 nm cause severe channel loss.

System III used a lensed dichroic coupler and the optical sources for the two channels were set at wavelengths 100 nm apart. As in system I, a first run of the analysis program indicated that the reflection channel (900 nm) of the coupler was not sufficiently selective. A long wavelength pass filter was required in front of the 900-nm channel to reduce crosstalk from the 800-nm channel. With the filter installed, in-band channel loss was about 30 dB with crosstalk 30 dB below the signal. Table 4.1-2 shows the matrix results of the system III analysis after the filters were added.

4.2 Detailed Sensitivity Analysis Factors

The detailed sensitivity analysis for the Air Force systems I, II, and III considered variations in key parameters on the system performance. Even though many papers exist concerning the design, fabrication, and operation of optical wavelength multiplexing components, little published work is available for evaluation of wavelength multiplexing systems. There is a great need for

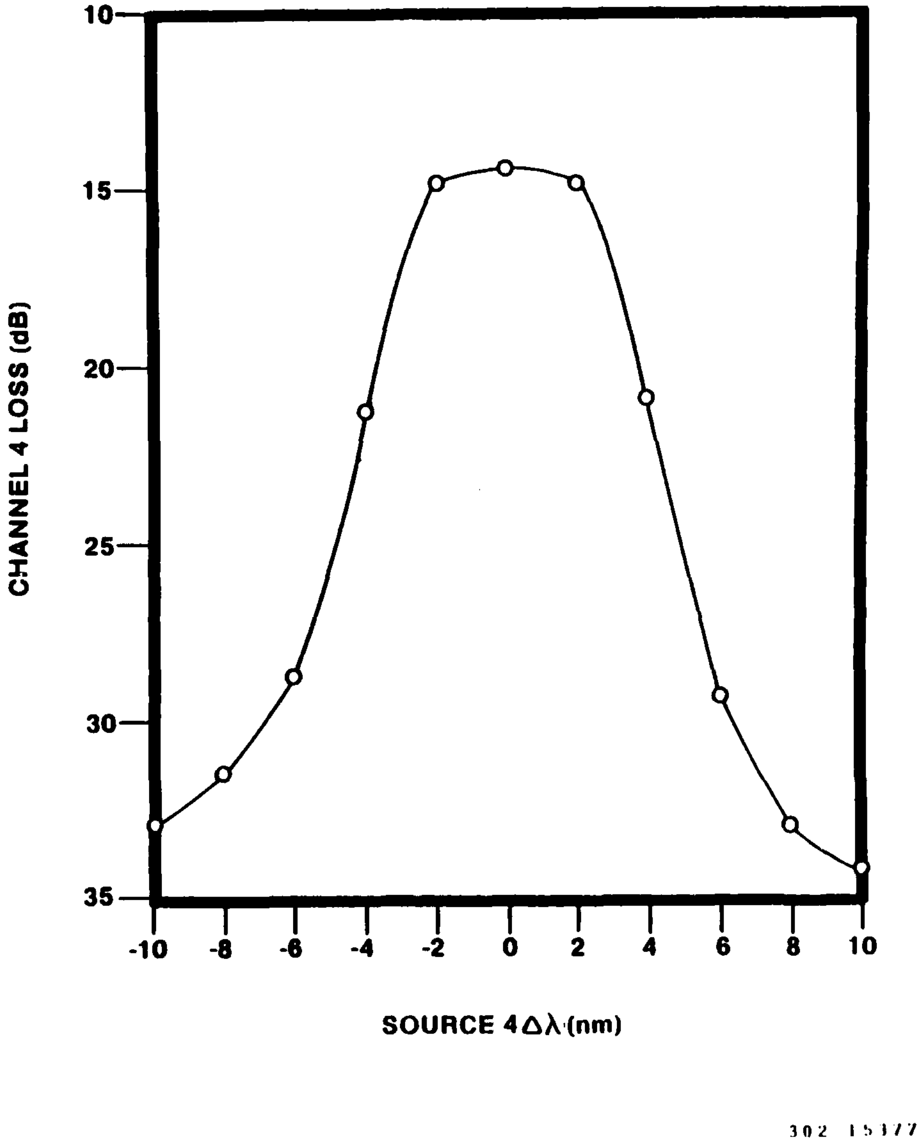


Figure 4.1-1. Air Force System II; Loss in Channel 4 as a Function of Source 4 Wavelength Drift.

Table 4.1-2. Air Force System III Insertion Loss in dB.

Sources	Detectors 1	Detectors 2
1	30.26	59.53
2	58.30	31.71
Total Crosstalk	-58.30	-59.53

serious wavelength multiplexing system analysis and comprehensive experimental evaluation of prototype systems usable in an avionics environment. While work is needed in all areas of system reliability, this subsection is limited to an analysis of system performance as a function of temperature.

4.2.1 Effect of Temperature on Fiber

Work at ITT EOPD[1] and other organizations[2 3] has shown that cabled fibers are capable of operating over the military temperature range. These studies also show that certain fiber types are not acceptable choices for the military temperature range. For example, the performance of plastic clad silica fiber begins to degrade rapidly around -30°C. The numerical sensitivity analysis does not include any effects from fiber degradation. The study assumes that a fiber type will be chosen that does not degrade with temperature.

4.2.2 Effect of Temperature on Couplers

A collection of journal papers on grating and dichroic types of multiplexers was scanned for information on device sensitivity to temperature. None of the papers contained any data on temperature or mechanical stability. The assumption is that the mechanical design of the grating and dichroic multiplexers can be realized in a manner so that temperature induced optical changes in the multiplexer are negligible. Unpackaged dichroics vary their cutoff frequency by only 1% over a 100°C range.

4.2.3 Parameters To Be Varied in Analyses

OCAP was available for evaluating system performance as a function of temperature. As explained in the previous paragraphs, multiplexer performance was expected to remain constant with temperature. Temperature variation, in turn, affected two parameters, source wavelength and source power output. These parameters were varied individually and in the coupled mode. This allowed prediction of performance on systems which might use feedback to stabilize source power and/or source frequency.

OCAP characterizes system components according to their spectral response. Laser sources are difficult to accurately characterize because their optical spectra vary with bias, modulation, coupling, temperature, and other parameters.

While the unmodulated spectral line width of a true single-mode laser may be on the order of 0.05 nm, many factors may increase line width. Work done at ITT's Standard Telecommunications Laboratory (STL) by R. E. Epworth,[4 5 6] which characterizes semiconductor laser temporal and spatial coherence, indicates that individual longitudinal line widths may become as large as 0.3 nm when modulated. In addition, even the best "single" longitudinal mode lasers often have two to three modes. Often lasers exhibiting one to three modes may exhibit many longitudinal modes when modulated. For example, a multilongitudinal mode laser with 10 modes spaced at 100 GHz would exhibit a 5.6 nm spectral width. The optical spectrum may drift with temperature; 0.6 nm/°C is not uncommon. Even if the laser is temperature stabilized by an external cooler, any perturbations to the cavity temperature are only damped by thermal time constants.

4.2.4 Source Spectral Broadening

The discussion of optical source spectral broadening is limited to two areas in the sensitivity analysis. A semiquantitative analysis examining possible unwanted injection locking is considered because laser spectral widths may become large. Data runs 2 and 3 for system II each include a single source (source 3) which has been spectrally broadened. The line width of the spectrally broadened source is set at 5 nm as compared with the nominal width of 1 nm for the other sources.

4.2.5 Injection Locking

Many designs for grating multiplexers utilize a linear array of fibers. This linear array includes the output fiber as well as all the input fibers. This technique simplifies device construction and the fiber alignment procedure. Many recent designs place the output fiber adjacent to the input fibers. In a system employing laser sources it is possible that injection mode locking could degrade system performance.

Consider a hypothetical system where channel spacing is set at 12 nm. Suppose temperature changes or aging shortened the wavelength of the second laser by about 12 nm. This would cause the output of the second laser to be coupled back into the first laser. The possibility then exists that the first laser would injection lock to radiation from the second laser. (See Figure 4.2.5-1.) Any injection locked output from the first laser would be in the correct spatial location for optimum coupling into the transmission output fiber. Thus, channel 1 would carry information intended for channel 2.

In addition, some coupling might occur from laser output of devices which are shifted by some integer multiple of 12 nm. The degree of coupling would depend upon the width of the laser gain curve and the relative strength of the coupled spectrum from laser number 2.

A semiquantitative argument is given to show that a probability exists for mode locking to occur, at least with some laser types. Consider a multimode laser exhibiting 10 modes and having a mode spacing of 100 GHz. Each longitudinal mode may have a width of 50 GHz. Consider the case of Figure 4.2.5-1 where all the lasers

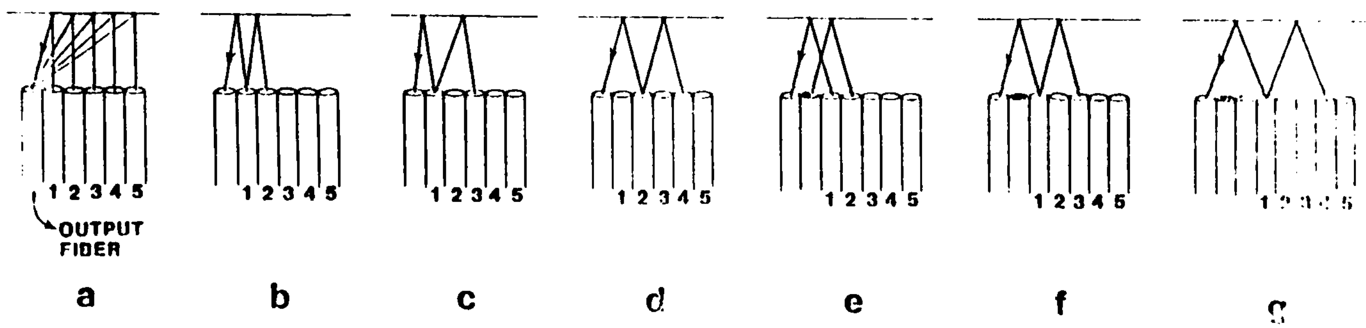


Figure 4.2.5-1. Possible Optical Paths for Injection Locking.

except laser 2 are operating correctly. The nominal channel spacing will be 12 nm. The normal operating spectrum is shown in Figure 4.2.5-2.

A reasonable wavelength shift with temperature drift is 0.6 nm/°C. Thus, an 11° temperature shift could cause the optical spectra to overlap with that of the next laser. The probability for injection locking with such a multimodal device would appear to be high enough that burst errors could become a problem. Multimode lasers are in general much more susceptible to injection locking than are single-mode devices. However, modal noise will increase as the number of longitudinal modes is decreased.

The possibility for undesired injection locking suggests a better grating multiplexer design might have one or more dummy fibers between the output fiber and first channel input fiber. While such a multiplexer (sketched in portions e, f, and g of Figure 4.2.5-1) is still subject to possible injection locking, there are fewer physical combinations which allow injection locking at wavelengths where they can couple into the output fiber. In addition, events which might lead to injection locking require greater wavelength deviation. The use of one or more dummy fibers allows the option of sensing any stray radiation that might be present if a source drifted from its nominal wavelength. While ITT EOPD is not aware of any papers which report a problem with undesired

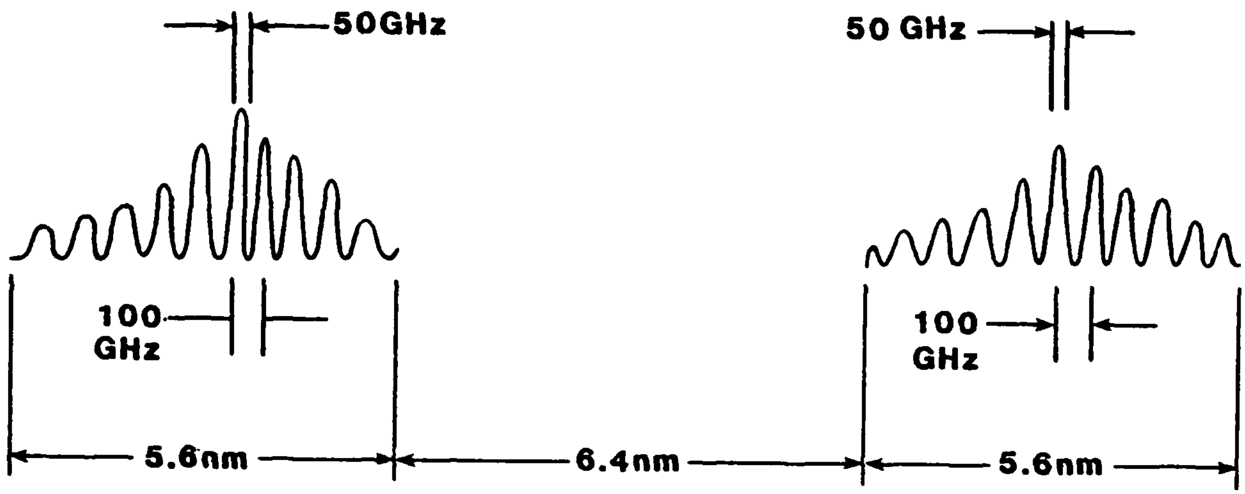


Figure 4.2.5-2. Laser Operating Spectrum.

injection locking, the possibility of such an event should be considered.

4.2.6 Laser Packaging

An additional problem that might arise in a wavelength multiplexing system is the variation of laser coupled power as a function of temperature. Many manufacturers utilize lenses in coupling from the laser to the fiber. Some, however, employ butt joining with the optical radiation being incident at a right angle to the fiber face. Such packaging may utilize materials having dissimilar temperature coefficients for coupling the laser and fiber. Thus, a change in temperature will modulate the external cavity length. Some planar packages vary output intensity by as much as 30% over a 3°C temperature change. Other packages utilizing butt joining may only vary 30% over a 30°C temperature range.

4.3 System Simulation Results

In system I, system II, and system III, three parameters are allowed to vary. These parameters are center frequency, power, and spectral width. The source center frequencies are varied according to temperature changes. The coefficients of temperature sensitivity are suggested by the literature. The power is allowed to vary with temperature using an exponential to approximate rates of 10% to 20%/10°C. Some of the data runs for system II were executed with one source having a wider spectral width than the nominal width of 1 mm. This allowed the effect of increased laser spectral line width to be quantified.

For systems I and III which employ light emitting diodes (LED), the optical spectrum was varied 2 Å-3 Å/°C over the temperature range -60°C to +120°C. Power was allowed to vary 1%/°C. The performance of system II which utilizes single-mode lasers with 1-nm line widths was studied as source center wavelength was varied from nominal values to ±12 nm in 1-nm increments. Power was varied 2%/°C. Two data runs were made with one of the sources replaced by a device having a 5-nm line width. While four data runs were made for system I, four data runs for system III and three data runs for system II, only the worst case performance data run is shown graphically.

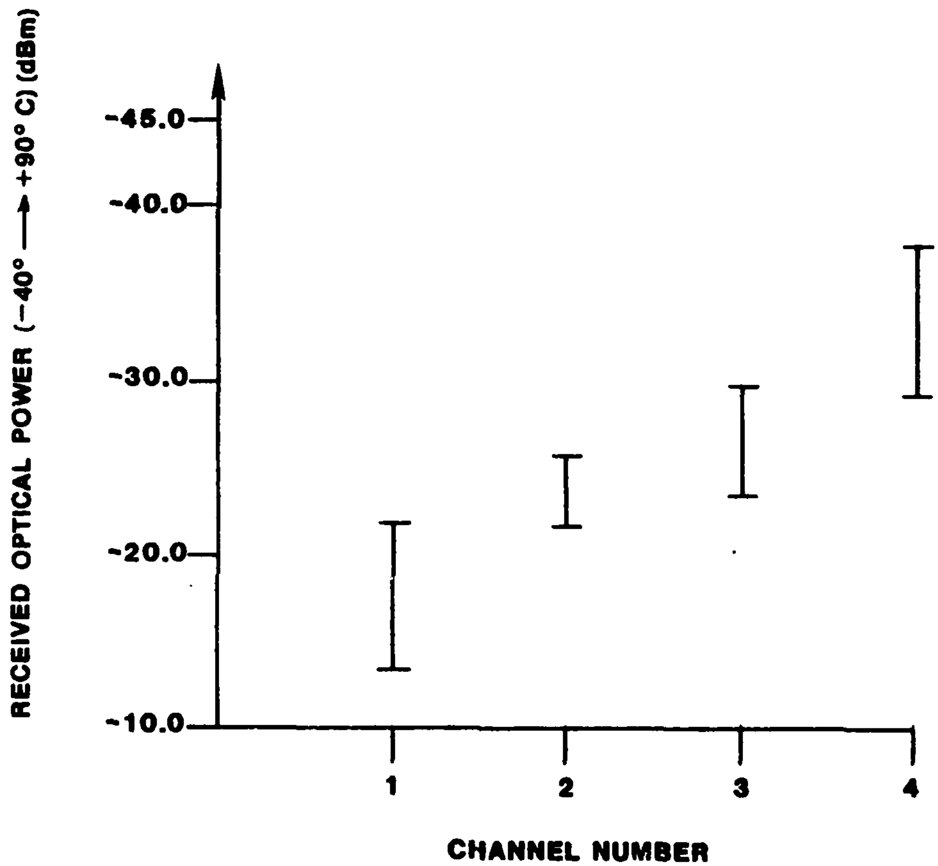
4.3.1 LED Systems

Four data runs each were made on systems I and III. Data run number 1 varied only the source center frequency. In this as in each subsequent case the entire optical modulation envelope is varied with the center frequency. The sources are all assumed to have their specified wavelength and power at +20°C. The wavelength was varied 2 Å/°C over the range -60°C to +140°C. The wavelength of all the sources was varied in concert. Data run number 2 varied wavelength by 3.5 Å/°C over the -60°C to +140°C range. Data run number 3 varied power approximately 10%/10°C over the same temperature range. Data run number 4 varied wavelength by 3.5 Å/°C and power by 10%/10°C.

4.3.1.1 System I

System I performed well over all conditions. Figures 4.3.1.1-1 and 4.3.1.1-2 show results for run number 4. In this data run as in all data runs there is sufficient optical power under all conditions. The worst case dynamic range of an individual channel is limited to only 9 dB over the -40°C to +90°C operating range of the system. For all the data runs the worst case of power crosstalk ratio over the operating range is 15.2 dB which easily allows a 10^{-9} bit error rate (BER). Even at 10 dB crosstalk ratio, it is necessary only to increase the power in the desired channel by 2 dB or less to achieve a BER of 10^{-9}. At 100 Mb/s, only -60 dBm received optical power is needed to achieve a 10^{-9} BER. The minimum received optical power for all the data runs is -37.7 dBm leaving a received power margin of over two orders of magnitude.

The worst case dynamic range over all the receiver channels of 23 dB was achieved. This is a value that could be realized allowing identical receivers to be used at each receiving port. If feedback were utilized to stabilize output power, the required dynamic range at a given port would be <4 dB for data run number 2 where only wavelength varies 3.5 Å/°C. A receiver having 18 dB dynamic range would be sufficient for all receiver ports. In



302 15864

Figure 4.3.1.1-1. System I - Data Run Number 4 (View 1). The height of the bars is the required dynamic range.

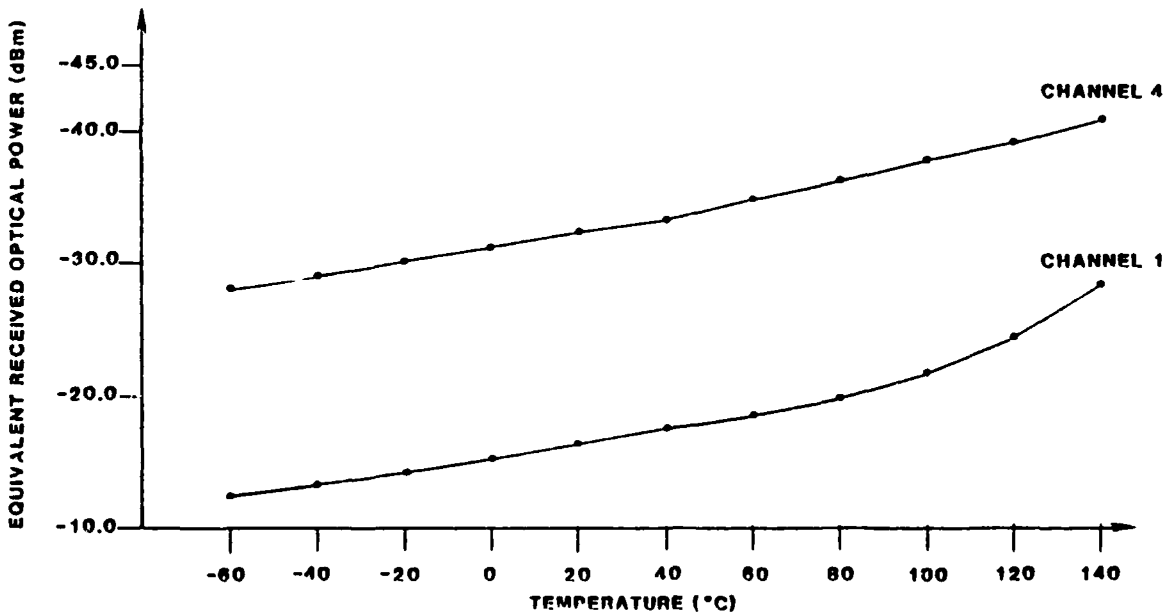
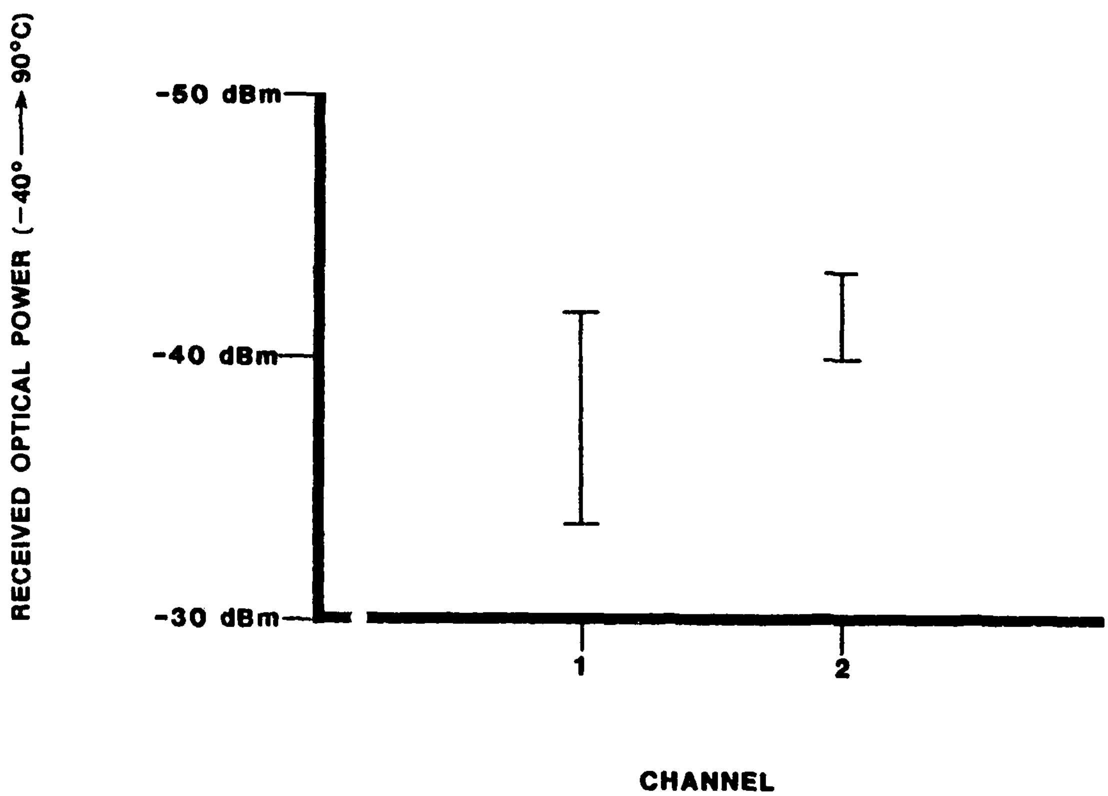


Figure 4.3.1.1-2. System I - Data Run Number 4 (View 2).

system I there is a great variation in received power from channel to channel. This is due to two factors. The light emitting c des have progressively lower power as channel number increases, and higher channel numbers have a high attenuation because of additional path loss in the dichroic couplers. Development of higher power long wavelength light emitting diodes and designing the dichroic couplers so that the lowest power light emitting diodes experience the lowest coupler attenuation would reduce the dynamic range requirements placed on the receivers. In this case it may even be desirable to reduce power in the short wavelength sources if the receiver dynamic range specification is difficult or expensive to achieve.

4.3.1.2 System III

System III is a very well behaved system. The dynamic range required by the conditions of data run number 4 is only 10 dB for a receiver which would operate over the required temperature range. The 10 dB in dynamic range is sufficient for both receiver ports. The addition of feedback to maintain a constant power only reduces the dynamic range required by a receiver capable of operating at both receiver ports by 2 dB. Figures 4.3.1.2-1 and 4.3.1.2-2 illustrate this good performance.



102 15867

Figure 4.3.1.2-1. System III - Data Run Number 4 (View 3). The height of the bars is the required dynamic range.

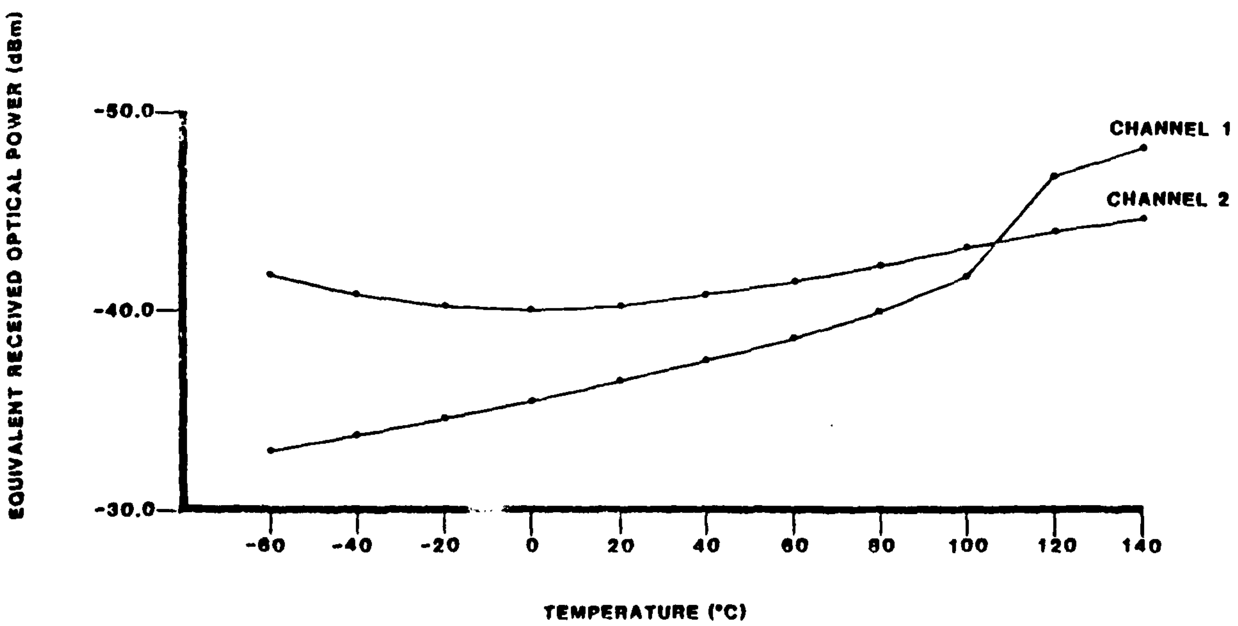


Figure 4.3.1.2-2. System III - Data Run Number 4 (View 4).

4.3.2 Laser Systems

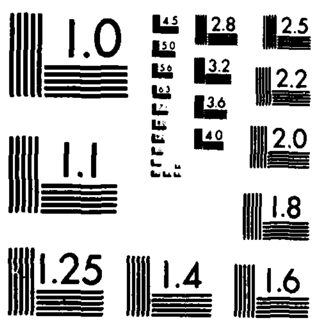
System II differs significantly from systems I and III because it utilizes laser sources. As in systems I and III there is always adequate received optical power; however, the system begins to degrade because of channel crosstalk. A 10 dB signal power to crosstalk power was set as an adequate system specification. Even with a typical avalanche receiver the optical power penalty incurred at 200 Mb/s is <2 dB.[7] This data assumes that the crosstalk data is not correlated with the desired channel data. The 2-dB optical noise power penalty ensures a BER of 10^{-9}. While the minimum required optical power for a given data rate depends on receiver design, a conservative estimate would require -52 dBm for a 300 Mb data channel having a BER of 10^{-9}. It is clear from the data of Figure 4.3.2-1 that there are always at least two orders of magnitude excess optical power for the tabulated data. Thus, the required 2-dB optical noise power penalty is insignificant.

Data run number 1 holds the optical power of the source constant while varying the lasers' optical frequency. This range of ±12 nm would cover a temperature span of approximately +40°C if the spectral coefficient were 0.3 nm/°C or +20°C for a coefficient of 0.6 nm/°C. The crosstalk limit of 10 dB is exceeded when the sources are shifted >-6 nm or more than +8 nm. For a spectral coefficient of 0.3 nm/°C, this corresponds to a temperature variation ranging from -1°C to +44°C. The maximum dynamic range

AD-A125 749 A STUDY OF WAVELENGTH DIVISION MULTIPLEXING FOR AVIONICS APPLICATIONS..(U) ITT ELECTRO-OPTICAL PRODUCTS DIV ROANOKE VA J C WILLIAMS ET AL. AUG 82 ITT-82-32-02 2/3

UNCLASSIFIED AFWAL-TR-82-1118 F33615-81-C-1481 F/G 9/3 NL

M-2



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

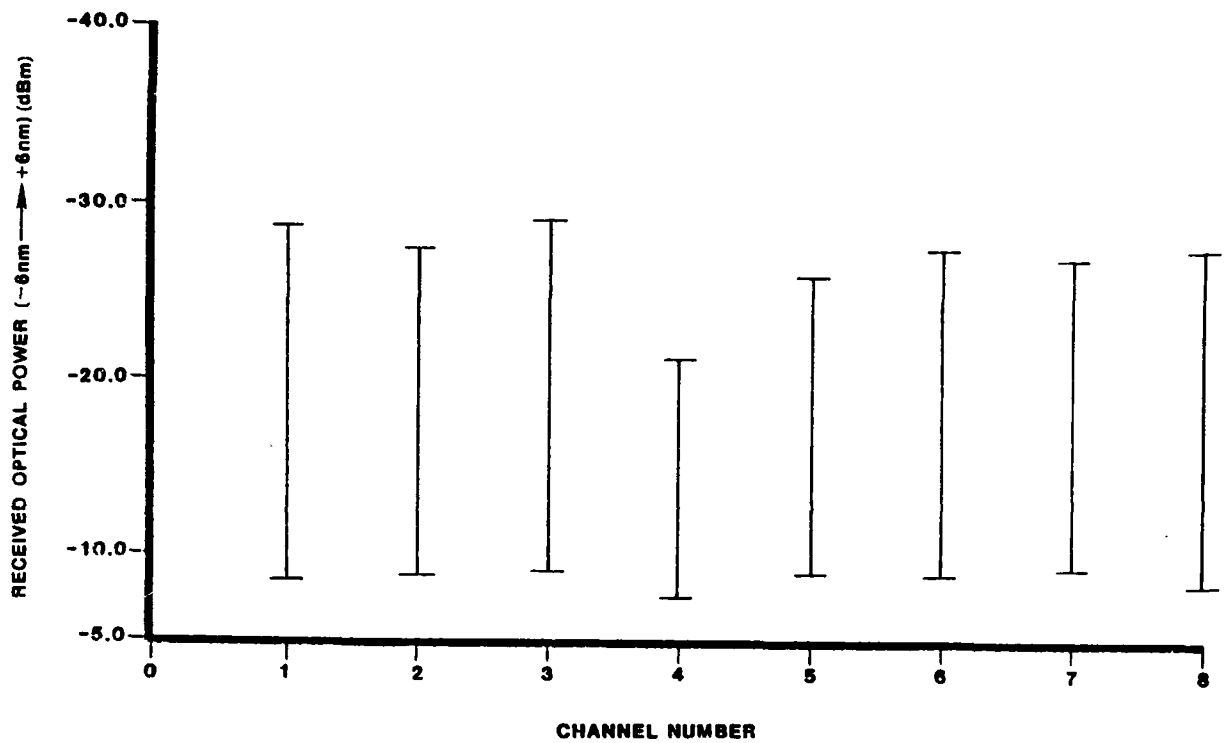


Figure 4.3.2-1. System II - Data Run Number 3. The height of the bars is the required dynamic range.

required for any channel is 21 dB. The required dynamic range of a receiver capable of operating at all receiver ports is 22 dB. System II fails in each case because of excess crosstalk power. The received optical power in the desired channel is sufficient even when the input optical spectrum is shifted by a full channel spacing. It appears that spontaneous radiation from the lasers is sufficient to provide adequate received power in the desired channel even when the peak of the stimulated emission is centered in an adjacent channel. In data run number 1 the worst case received optical power in the desired channel ranges between -31 dBm and -33 dBm even when the stimulated emission peak is shifted by +12 nm or -12 nm. The channel spacing in system II is 12 nm.

Data run number 2 is identical to data run number 1 except that the source width of laser 3 is 5 nm rather than 3 nm. Data run number 2 fails to meet system performance requirements because of excessive crosstalk power after source wavelengths are shifted by more ±6 nm. In addition there is an extra 8 dB optical power penalty in channel number 3 at the -6 nm wavelength offset. The dynamic range of a receiver capable of operating at each receiver port is reduced by about 2 dB from that of data run number 1. This reduction in the required receiver dynamic range is at the expense of reduced system operating range.

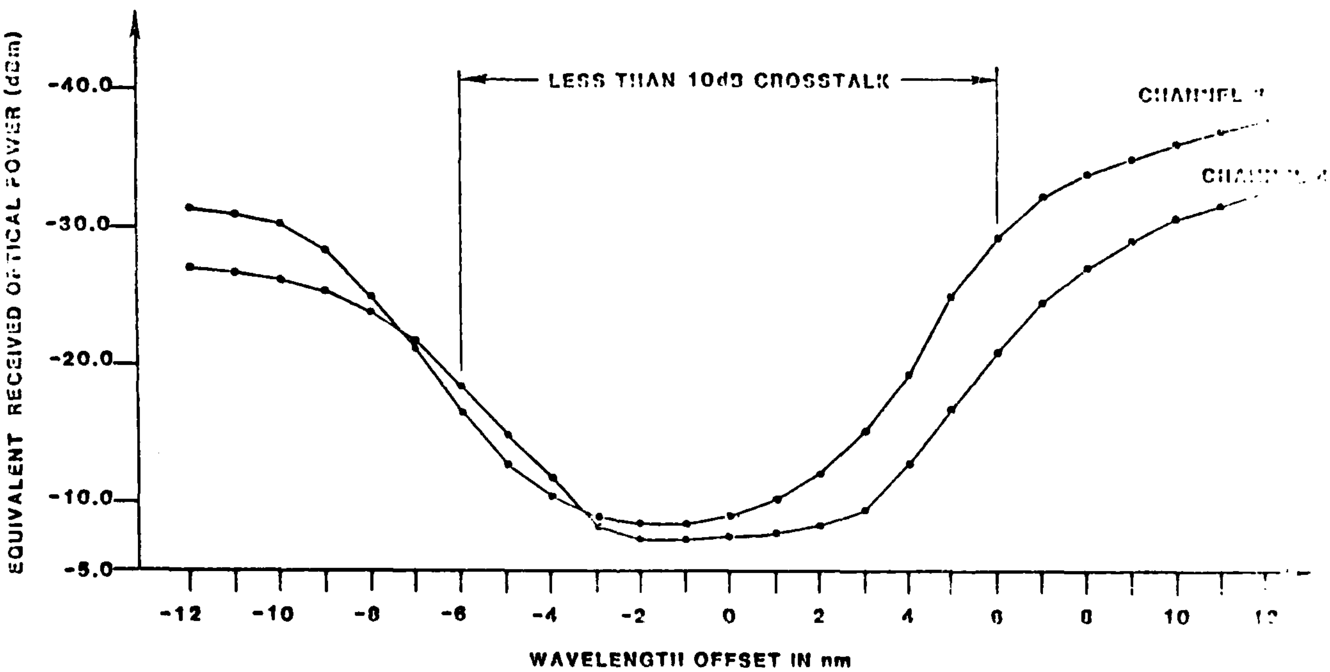


Figure 4.3.2-2. System II - Data Run Number 3.

Data run number 3 is identical to data run 2 except that the power of the optical sources is varied by approximately 20%/10°C. Data run number 3, like run number 2, exceeds the 10 dB crosstalk limit after the ±6 nm wavelength shifts. This is shown in Figure 4.3.2-2. Data run number 3, however, requires >2 dB receiver dynamic range to compensate for the larger optical power deviations.

4.4 Sensitivity Analysis Conclusions

An immense amount of detailed information was produced during the system sensitivity analysis. The results showed that the OCAP program worked well, the Air Force base line system designs worked well, and that changes in key system parameters could easily be made and evaluated. Since changes in key parameters (for example, temperature of lasers) reduce the optical power and spectral selectivity changes, the analysis methodology developed can be used to investigate any parameter change effect which is analytically predictable or empirically known. The major problem in the use of OCAP is making the best decisions about what parameters to vary and how much to vary them. At this point in the development of WDM technology for avionics, some actual "hardware experience" would be most helpful to direct the use of the analysis program.

A summary of the system sensitivity analysis results is given in Table 4.4-1.

Table 4.4-1. System Analysis Results.

Item	Results
Optical Circuit Analysis Program (OCAP)	• Works well, provides for selection of system, components, and changes to nominal component losses and wavelength selectivity • Needs more specific system degradation inputs
Air Force base line system designs	• Systems I and III modified to reduce crosstalk • All systems work with good performance margins • System II has wide power margin but tight crosstalk margin; use of light emitting diodes may be possible • System III has the least sensitive overall performance
Sources	• Injection locking of lasers may be a problem
Couplers	• Temperature sensitivity may not be a problem

23202

5.0 DEMONSTRATION SYSTEM DESIGN

The goal of this activity was to develop a design for a WDM demonstration system which is both compatible with the Airborne Electronic Terrain Map System (AETMS) interface and capable of serving as a general purpose demonstrator through appropriate software and/or hardware modifications.

The objective of this report section is to present the design which has been developed for a WDM demonstration system and the rationale used during the design development. The WDM demonstration system described in this report is also documented in a Level B1 Prime Item Development Specification prepared for delivery at the same time as this technical report.

The WDM demonstration system design presented in this report has been developed with two major purposes in mind. These are (a) demonstration of WDM equipment using (primarily) the AETMS interface and (b) testing of WDM system optical components. The demonstration system is a "laboratory bench" piece of equipment which can be programmed to operate in AETMS, self-test, or individual channel modes. Demonstration system flexibility is provided to allow the system to test a wide variety of WDM components using different signal formats. The WDM demonstration system design is divided into mechanical, electrical, and optical areas. The design effort, per the contract requirements, was directed toward generation of a Level B1 Prime Item Development Specification. Detailed design of the system, sufficient to actually fabricate the system, is beyond the contract scope.

5.1 Demonstration System Design Overview

The WDM demonstration system is a laboratory bench tool which must demonstrate WDM systems and test WDM system components. In the design of the system, requirements of the AETMS interface, self-test operation, and single-channel operation drive the selection of system functional modules. The organization of these modules into the demonstration system was guided by the desire for system flexibility sufficient for use with any of the Air Force base line WDM systems.

The mechanical concept for the WDM demonstration system is shown in Figure 5.1-1. System electrical and optical modules fit into standard 19 in rack-mountable enclosures. For a selected demonstration or test, the modules will be electrically and optically interconnected with jumper cables. Power supplies for the electrical modules are contained within the rack-mountable enclosures. The optical modules are passive. Table 5.1-1 lists the types of modules which are necessary to meet currently known Air Force requirements. Future requirements can be easily accommodated with additional modules that have extended capabilities.

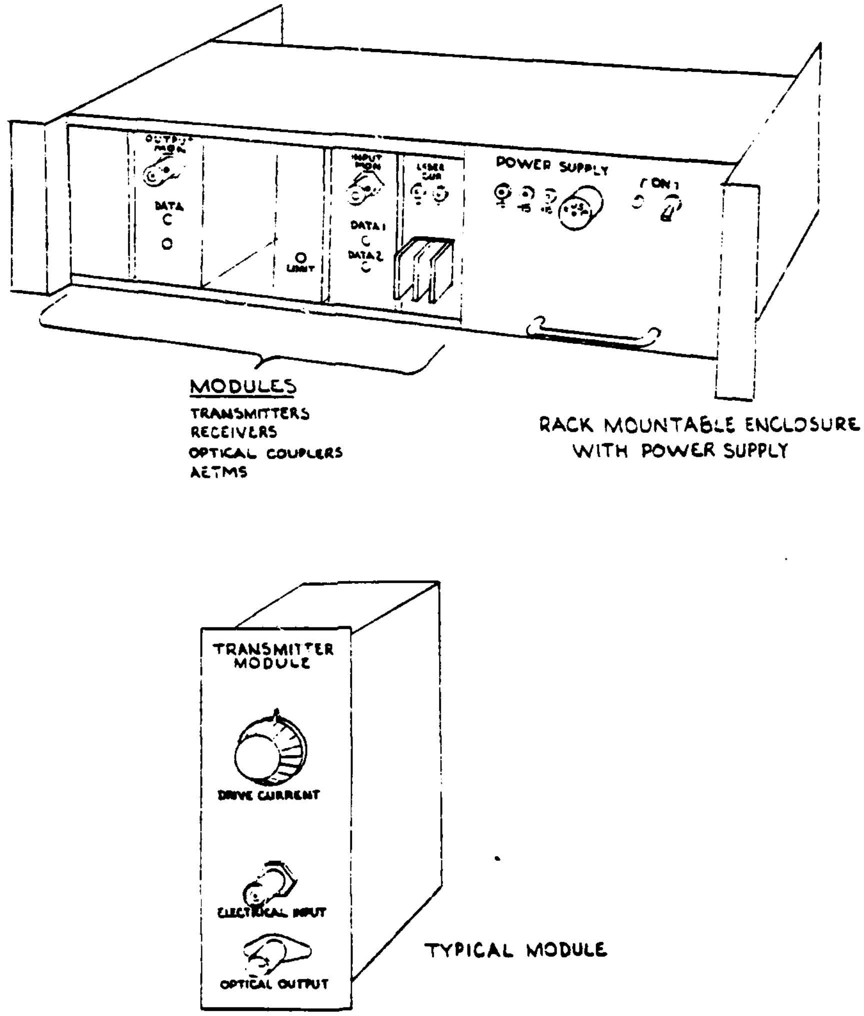


Figure 5.1-1. WDM Demonstration System Mechanical Concept.

23202

Table 5.1-1. WDM Demonstration System Module Types.

Electrical Modules

Transmitter, LED

Transmitter, laser diode

Receiver, pin detector

Signal generator, AETMS

Transmitter interface, AETMS

Receiver interface, AETMS

Signal receiver and tester, AETMS

Optical Modules

Coupler, wavelength selective

Coupler, nonwavelength selective

Attenuator, nonwavelength selective

Note: Data rate and wavelength specifications would have to be applied to most modules; these depend on the system being demonstrated.

An example of modular system design along the lines selected is a multichannel (but not WDM) communication system built recently by ITT EOPD. Figures 5.1-2 and 5.1-3 show the rack-mountable enclosure and an example of a module used in this system. Transmitter, receiver, encoder, and decoder modules can be installed as needed in the enclosure. The WDM demonstration system design described in this report would require approximately four module enclosures. One enclosure each would house transmitters and receivers, one enclosure would hold the AETMS electronics, and one enclosure would hold the optical components.

5.2 Electrical Design Overview

In developing the wavelength division multiplexing demonstration system, initial guidelines were identified in order to establish the operating requirements of the hardware. The driving goal of the system design was the development of laboratory equipment that demonstrates and exercises fully a WDM fiber optic system.

The development system has three modes of operation: (a) direct interface to an AETMS system, (b) a self-test mode with internal AETMS format pseudorandom data generation, and (c) local test capability where a data stream can be introduced directly into the transmitters and can be removed directly following the receiver preamplifiers for BER analysis.

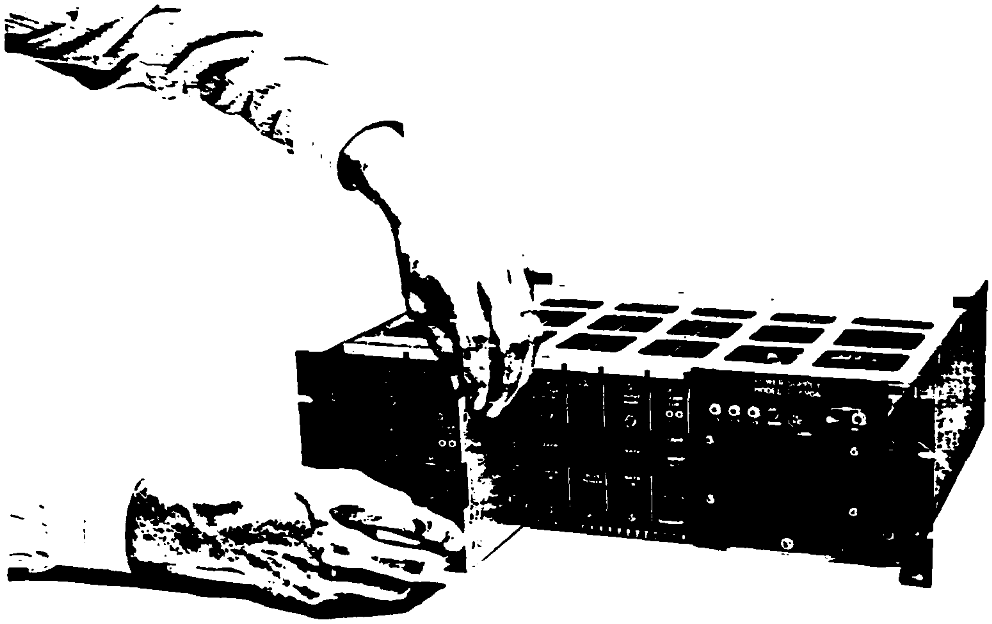


Figure 5.1-2. Rack-Mountable Modular Communications System.

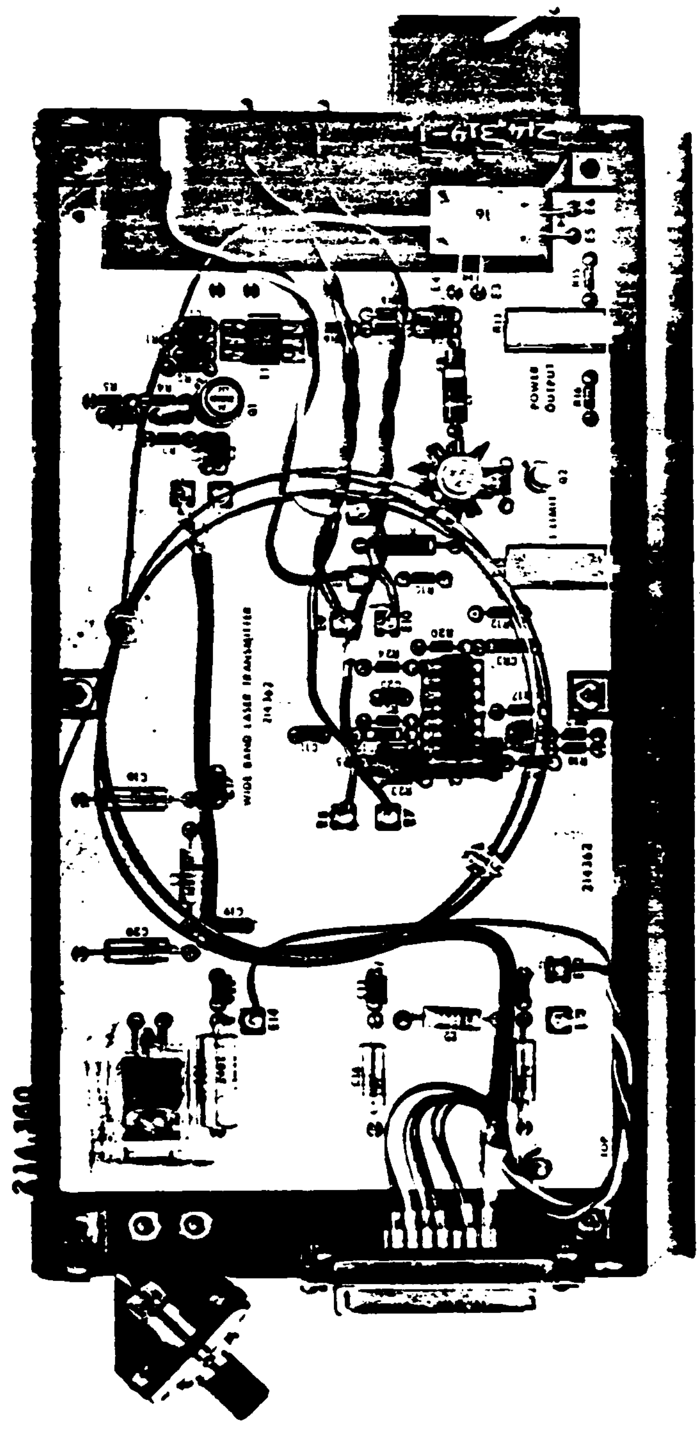


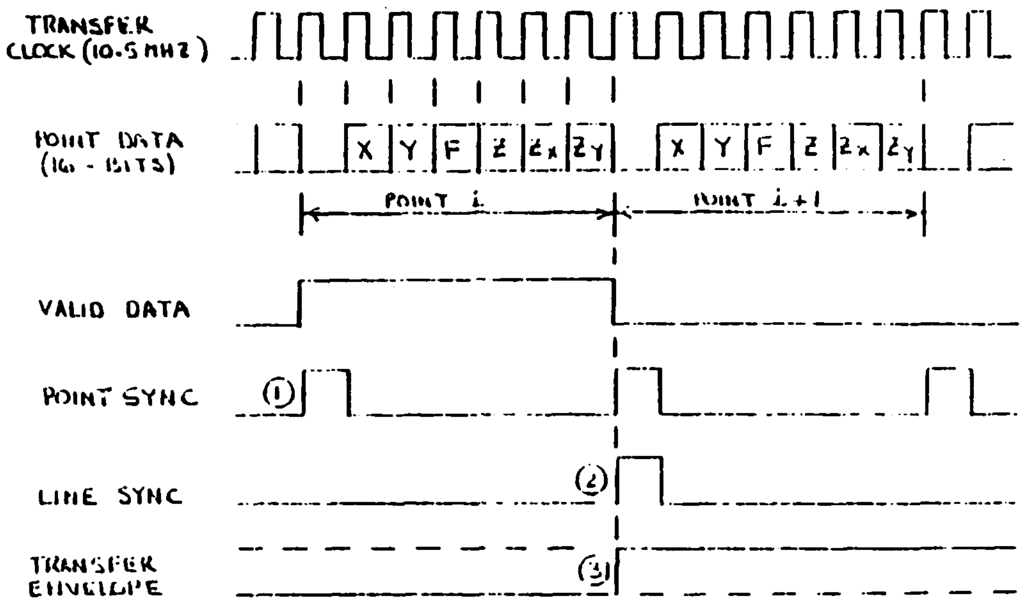
Figure 5.1-3. Laser Transmitter Module.

5.2.1 AETMS Mode

A point-to-point WDM fiber optic link utilizing four wavelengths capable of transmitting the data and clock from the AETMS system was developed. A prime consideration in the design was to minimize the electronics development and complexity while designing a system that interfaces directly to the AETMS system. Thus, the purpose of the WDM demonstration system is not to realize the ultimate in electrical digital multiplexing sophistication, but rather to demonstrate the performance characteristics of the optical components and optical wavelength multiplexing capability in a practical system such as the AETMS. Four optical wavelengths in the WDM demonstration system were deemed to be technically realizable while being sufficient to demonstrate the concept.

The AETMS interface is a parallel data interface transferring data continuously at a 10.5 MHz rate. The interface consists of 16 bits of parallel data, a continuous 10.5 MHz transfer clock, and 4 parallel control lines. Data is transmitted in groups, "points," which are seven clock cycles long. "Points" are framed by the point sync, which is one of the four control lines (see Figure 5.2.1-1 for the AETMS interface timing diagram).

Upon reception of the data at the AETMS interface, data must be serialized and multiplexed to drive the four fiber optic transmitters. The multiplexing scheme selected is illustrated by the



NOTES: (1) INDICATES THE BEGINNING OF A POINT TRANSFER

(2) INDICATES FIRST POINT OF A SCAN LINE

(3) ENVELOPES VALID POINT TRANSFER SIGNAL CHANGES STATE AT THE END OF A POINT TRANSFER

Figure 5.2.1-1. Interface Timing Diagram.

block diagram, Figure 5.2.1-2, and timing diagram, Figure 5.2.1-3. The clock signal is transmitted separately on one of the transmitters. The 16 bits of parallel data are serialized, divided into two 8-bit data streams, and transmitted by the second and third fiber optic transmitters. Finally, the control lines are sampled during the first clock cycle of each point. These four bits are serialized and transmitted by the fourth fiber optic transmitter.

In order to transfer the serial data, a higher frequency clock is generated. This clock will run at 84 MHz or eight times the AETMS transfer clock rate. It is this clock, phase locked to the AETMS transfer clock, which will be transmitted over the fiber optics. For transmission of the AETMS control lines, a guaranteed rising edge will occur at the start of every point by assigning the point sync signal to the first bit of the data stream. This sync pulse can be used to reframe the data and clock at the receive end of the system. Once the incoming AETMS data has been serialized and multiplexed the four data streams will be scrambled. This will be done to ensure transitions in the data and therefore allow for the proper performance of the fiber optic transmitters and receivers.

The use of the four optical wavelengths simplifies the electronic hardware in several ways. First, the division of the data into channels reduces the individual channel data rate. With decreased data rates come relief from the added cost and design problems

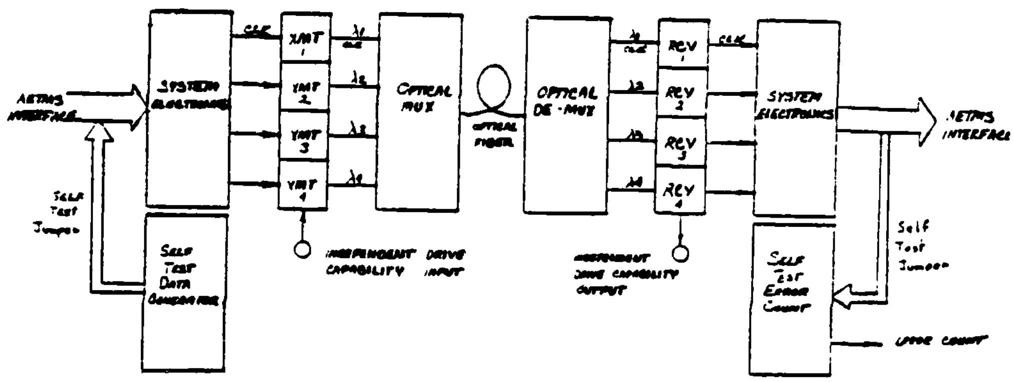


Figure 5.2.1-2. AETMS Multiplexing Scheme Block Diagram.

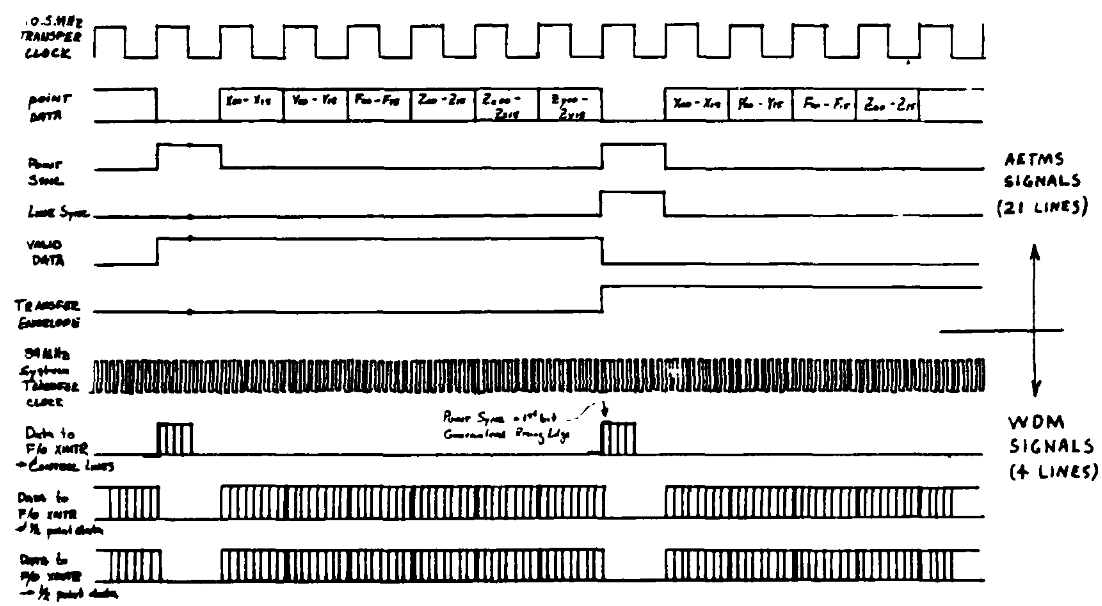


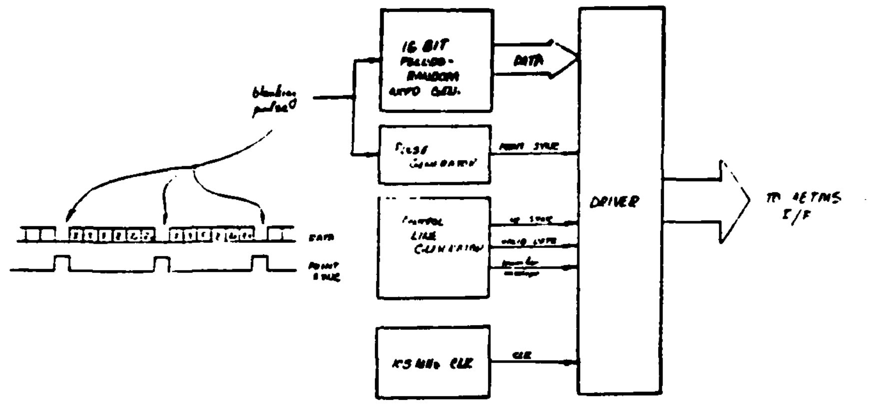
Figure 5.2.1-3. Multiplexing Scheme Timing Diagram.

associated with very high data rate electronics (>150 Mb/s). Second, by sending the clock and control signals through separate channels, the need for complex clock recovery and retiming circuitry is avoided.

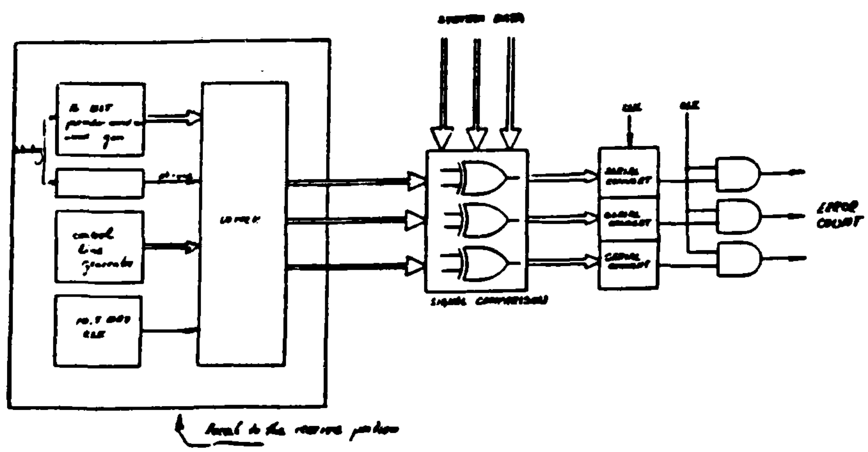
5.2.2 Self-Test Mode

In the absence of the Air Force AETMS equipment, the ability to test the WDM demonstrator system interface and associated electronics is desirable. Therefore, a self-test capability was provided (see Figure 5.2.2-1). Pseudorandom data in the AETMS data format will be generated at the transmit side of the WDM system. This data will consist of the 10.5 MHz transfer clock, 16 parallel lines of pseudorandom data "blanked" every 7 clock cycles to simulate the point data, and 4 parallel lines which are varied to simulate the control lines. The self-test interface will be coupled to the AETMS interface to inject data into the AETMS data link.

Test data, identical to the transmitted self-test data, will be generated at the receive end of the WDM demonstrator system. The data sent through the system will be compared on a bit-by-bit basis with the data generated at the receive end to determine if bit errors occur. Error counts will be generated. The data comparison and error counts will be configured in such a way that a separate error count can be tallied for each optical data channel.



a. Data Generator.



b. Error Checker.

Figure 5.2.2-1. AETMS Self-Test Operation Module Block Diagrams.

Switching between the AETMS mode and self-test mode will be accomplished by jumping with twisted-pair ribbon cable and multipin connectors between the self-test data port and the AETMS interface at both the transmit and receive terminals. This design is especially attractive as it allows the testing of the actual AETMS interface.

5.2.3 Individual Channel Mode

As a significant function of the system, the ability to test and evaluate the optical components must be provided. It must be noted that this goes a step beyond demonstrating the components as part of a working, static data link. Therefore, the WDM demonstration system will provide a separate driving capability to each fiber optic transmitter and a direct output from each fiber optic receiver.

This arrangement will allow the user to individually drive each transmitter by itself or with any combination of the other three transmitters. In addition to the performance evaluation capabilities of other operational modes, the individual channel mode enhances the ability to evaluate system performance parameters such as BER signal-to-noise ratio (snr) interchannel crosstalk, coupler performance, and multiplexer performance. The additional ability to individually vary the optical power output from each transmitter exists. This capability enhances the ability to evaluate the optical components.

5.2.4 Fiber Optic Transmitter and Receiver Performance

As part of the continuing work at ITT EOPD, a wide variety of fiber optic transmitters and receivers have been designed and built. The requirements for the fiber optic data link for the WDM demonstrator link are typical of systems developed in the past. The parameters specified for the fiber optic transmitters and receivers in the demonstration system represent an achievable design capable of evaluation and testing of the optical components of the WDM system.

5.2.4.1 Transmitter Performance

Four (in the case of AETMS) fiber optic transmitters will operate as part of the WDM demonstrator system. The transmitters will be electrically identical except for the choice of emitters and emitted optical wavelengths and will be switchable between two data inputs interfaces: (a) the AETMS data interface and (b) the individual channel data. Both data interfaces accept nonreturn-to-zero (nrz) coded data at ECL logic levels terminated in 50 Ω to -2 V. The data rate can vary from a maximum of 100 Mb/s to a minimum of 100 kb/s. The minimum operational data rate will depend on the low frequency content of the received data.

The choice of optical emitters was made to demonstrate a wider capability of the WDM components and system. The system will be configured using three injection laser diodes and one LED. The laser diodes will be used on the optical channels which transmit the transfer clock and point data. The control signals will be transmitted using an LED.

The choice of emitted optical wavelengths will be dictated by the requirements of the WDM. The laser will be biased at its threshold and driven to an optical output power of 500 μW. This optical power, nominally 500 μW, can be varied ±400 μW. Provisions will be made to temperature sense and stabilize the laser and to provide optical feedback for stability. The LED will have a nominal optical power output of 35 μW with the ability to vary ±10 μW.

5.2.4.2 Receiver Performance

Four (for the AETMS example) fiber optic receivers will operate as part of the WDM demonstrator system. The receivers will be electrically identical except for the (possible) difference in choice of detector wavelength of operation. The receivers will be switchable between two data output interfaces: (a) the AETMS data interface and (b) the individual channel data. Both data outputs will be nrz coded data at ECL logic levels terminated in 50 Ω to -2 V. The receivers will be wide bandwidth receivers accepting data from 100 Mb/s to 100 kb/s.

The receivers will use pin diodes as detectors. The pin diodes were chosen over avalanche photodiodes (APD) because the sensitivities required of the system were attainable with a pin, thus reducing cost, electronic complexity, and power supply requirements. For wavelengths from 760 nm to 1000 nm, silicon pin detectors will be used; for longer wavelengths, III-V detectors will be used.

The receivers will be wide bandwidth ac coupled receivers. They will utilize a low noise, balanced transimpedance front-end preamplifier. The use of a manual gain control will enhance system performance and simplify the electronics. The signal will be amplified in subsequent stages and drive an ECL output.

To avoid complex data realignment problems, care must be taken that the time delay through the receivers is uniform. Variations in delay must be less than 5% of a clock period. In addition, provisions will be made in each receiver to align the clock and data channels for the case of differential propagation delays between wavelengths of operation.

5.3 Optical Design

The optical design of the WDM demonstration system most carefully considered the avionics applications in which the Air Force systems would be used. Optical fiber, optical connectors, and optical couplers considered for WDM use are discussed in the paragraphs below.

5.3.1 Optical Fiber

The optical fiber selected for link use in most avionics applications is expected to be 0.28 (nominal) numerical aperture (NA), 100-μm/140-μm core/cladding diameter, all glass, semigraded-index fiber. This fiber is preferred because the large core diameter allows easy optical coupling and the bandwidth is sufficient for the short links necessary on aircraft. This fiber has been selected as the link fiber for the WDM demonstration system and therefore will be used to interconnect the optical couplers that a given system uses.

The optical fibers used between transmitters and couplers and receivers and couplers must be of different dimensions than the link fiber if optimum optical coupling is to be achieved. Optical coupling efficiency is maximized if power is transferred from a small fiber (small in the sense of NA, core diameter, and index profile parameter) to a larger fiber. To ensure that the WDM couplers in the system benefit from the "small to large" fiber connections, transmitter-to-coupler connections will be made with fiber smaller than the link fiber and coupler-to-receiver connections will be made with fiber larger than the link fiber. Fiber with (nominal) core/cladding diameters of 50 μm/125 μm and

200 μm/250 μm will be used in these locations, respectively. Figure 5.3.1-1 illustrates this use of fiber sizes in Air Force System III.

All fiber used to connect WDM demonstration system components will be in the form of single-fiber cable with a strength member. This form of the selected fibers is readily available from several suppliers.

5.3.2 Connectors

The Amphenol type 906 single-way optical fiber connector has been selected for the design. This connector was chosen because it has demonstrated a good performance and has been widely used on Air Force fiber optic systems. Installation is well understood and cable strength member tie-off is convenient. The modules of the demonstration system will be equipped with bulkhead type connectors on the front panels and intermodule connections will be made with single-fiber jumper cables which have connectors on each end.

5.3.3 Optical Couplers

The demonstration system couplers, both wavelength selective and nonselective, will be packaged in modules similar to those designed for the electronic items. The ports of the couplers will be brought out to Amphenol type 906 front panel connectors which will be clearly marked with the port designation.

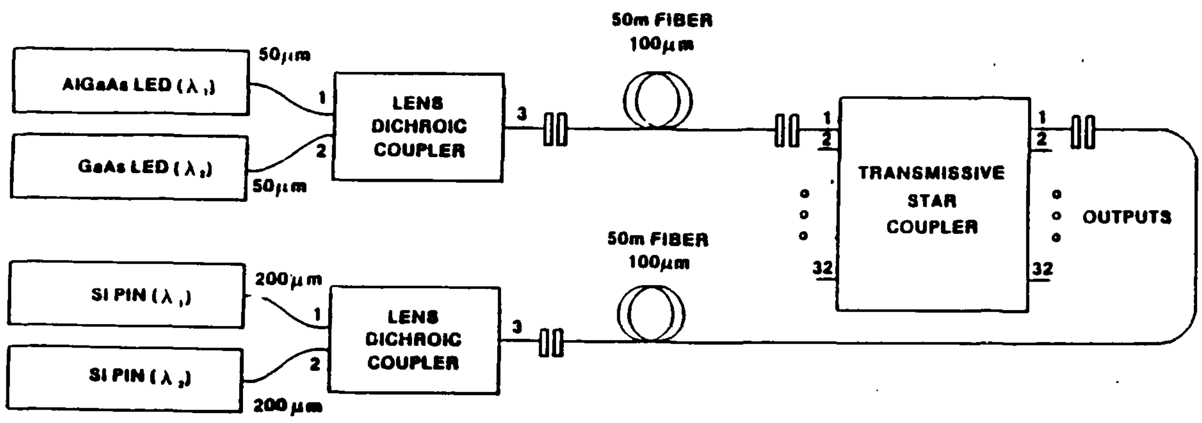


Figure 5.3.1-1. Air Force System III Illustrating Use of Different Size Fibers at Different System Points.

23202

5.3.4 Optical Modules for AETMS Mode Demonstration

The optical and electrical modules required in the WDM demonstration system will vary depending on the specific WDM configuration which is being investigated. For the AETMS mode, the required modules are listed in Table 5.3.4-1. The electro-optical or optical performance of these modules will allow operation of the interface with less than a 10^{-9} BER. Selection of the specific channel wavelengths and the coupler designs will be made at the time of the detailed design.

5.4 System Performance Parameter Monitoring

The WDM demonstration system provides the capability to monitor and display various system performance parameters which indicate the quality of the fiber optic communication links under test. Examples of the monitoring of these system performance parameters are given in this subsection. The specific parameters discussed are bit error rate, link delay, optical dynamic range, rise time, and power consumption. Flexibility of the WDM demonstration system makes possible any test which can be done on a nonmultiplexed fiber link in addition to tests unique to multiplexed links.

5.4.1 Bit Error Rate

The bit error rate (BER) of the system can be monitored with the system in either the AETMS self-test mode or the individual channel mode. In the AETMS self-test mode, bit error pulses available

Table 5.3.4-1. WDM Demonstration System Electrical and Optical Modules Required To Demonstrate the AETMS Mode.

Electrical Modules

Item	Quantity
Transmitter, channel 1	1
Transmitter, channel 2	1
Transmitter, channel 3	1
Transmitter, channel 4	1
Receiver	4
AETMS modules	Full set

Optical Modules

Item	
WDM multiplexer, 4 to 1 channels	1
WDM demultiplexer, 1 to 4 channels	1

at the error count outputs (see Figure 5.2.2-1) can be monitored by an external pulse counter. The BER of the system is then given by

$$BER = \frac{\text{number of errors}}{\text{total number of bits}} \tag{5-1}$$

For example, a 10^{-9} BER corresponds to one bit error in a 10.5 MHz data stream in a period of 95 s.

In the individual channel mode of demonstration system operation, a serial bit stream can be introduced at the local data input (BNC connector) of one of the transmitters. This data stream can later be recovered at the output of the appropriate receiver and tested with conventional BER equipment. An external clock would be used to clock the BER test equipment. It would be possible to operate all channels of the WDM system during this test to evaluate cross-talk effects on the channel under test.

5.4.2 Link Delay

The time delay through the link is determined by two portions of the link: the fiber cable and the transmit and receive electronics. For an average link the delay due to the fiber optic cable dominates the delay due to the electronics. However, in cases where the length of the optical cable in a link is very short, as in the AETMS demonstrator, the delay due to the system electronics is dominant.

The system time delay can be measured using the AETMS parallel data inputs (see Figure 5.4.2-1). A pulse introduced at one parallel data input is recovered at the corresponding parallel output. With care given as to the rate of pulse transmission and synchronization of the oscilloscope, the system time delay can be read directly (see Figure 5.4.2-2). A similar technique could be used to measure the link delay of a given channel in the individual mode of operation.

5.4.3 Optical Dynamic Range

The optical dynamic range measurements can be done in either the AETMS or individual channel mode of operation of the WDM demonstration system. Figure 5.4.3-1 shows the insertion of a calibrated variable optical attenuator into the optical link to be tested. Bit error rate equipment monitors the performance of the optical link as the attenuator is adjusted to vary the optical power from "receiver overload" to a "below receiver sensitivity" condition. The optical transmitter of the channel under test must be adjusted to provide an output power which will overload the receiver when the attenuator is adjusted for a minimum inserted loss.

5.4.4 Rise Time

The WDM demonstration system may be used to measure system rise time (RT) directly or on a component-by-component basis.

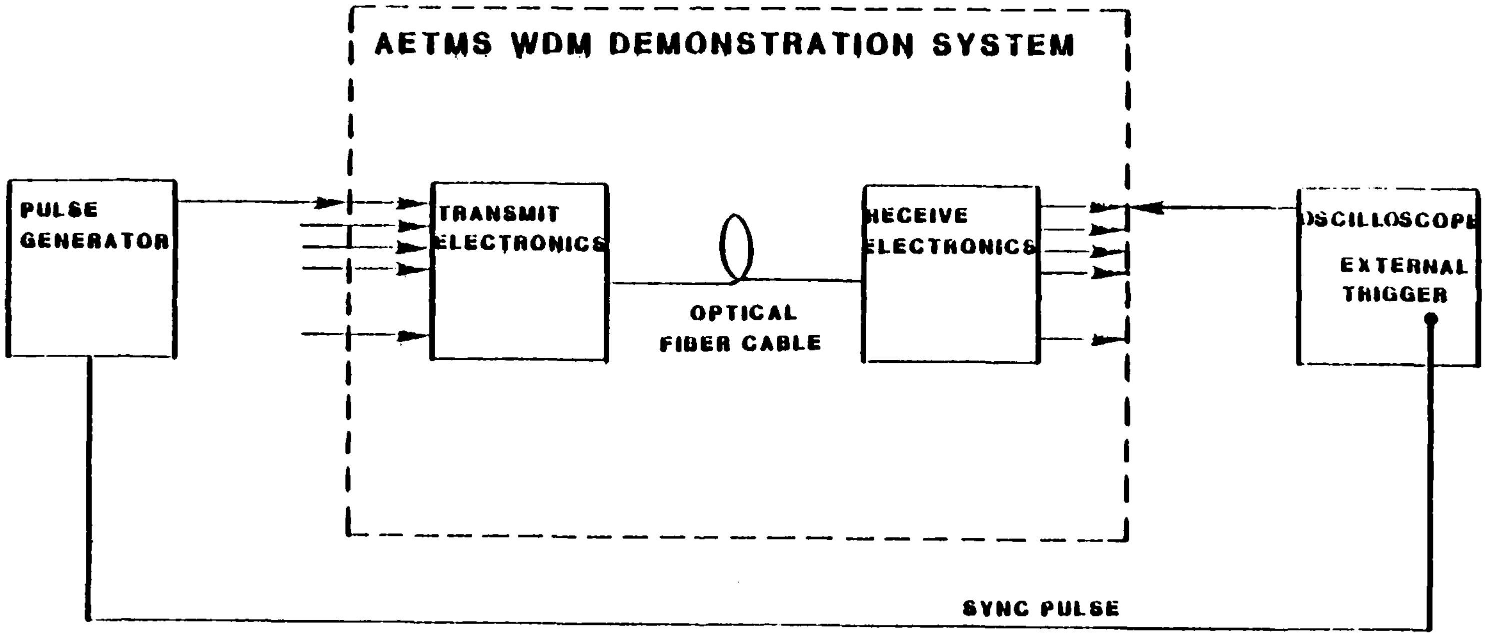


Figure 5.4.2-1. AETMS WDM Demonstrator Link Delay Test.

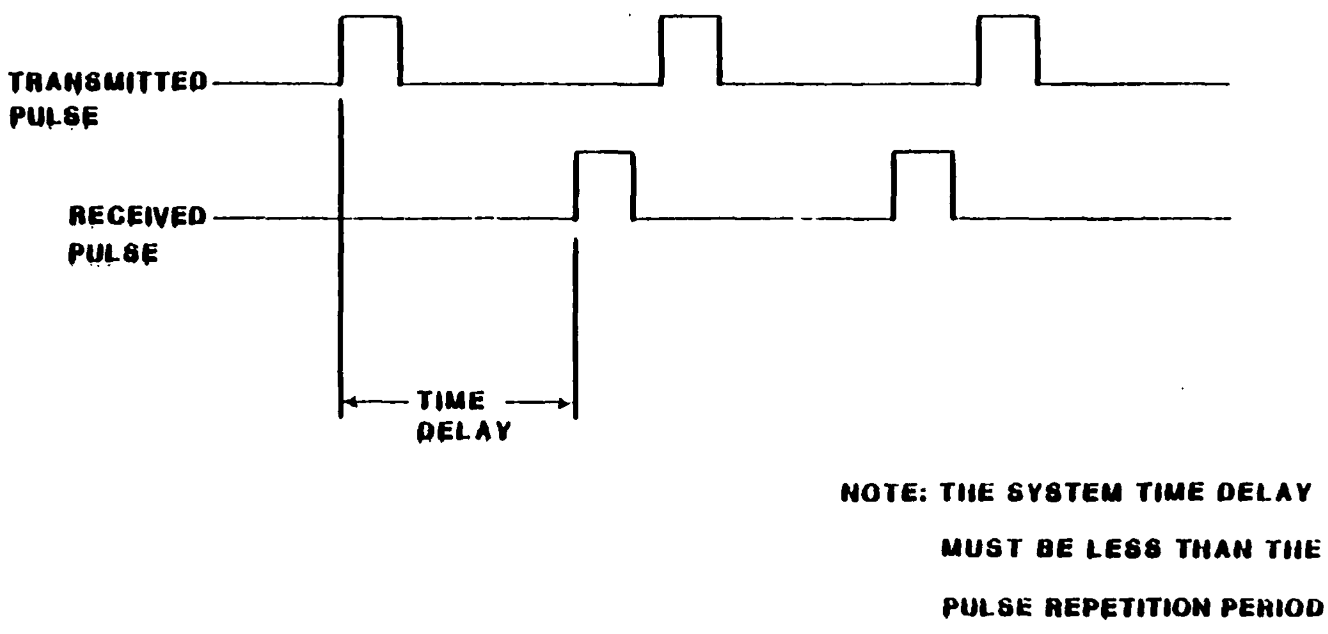


Figure 5.4.2-2. Link Delay Test Waveforms.

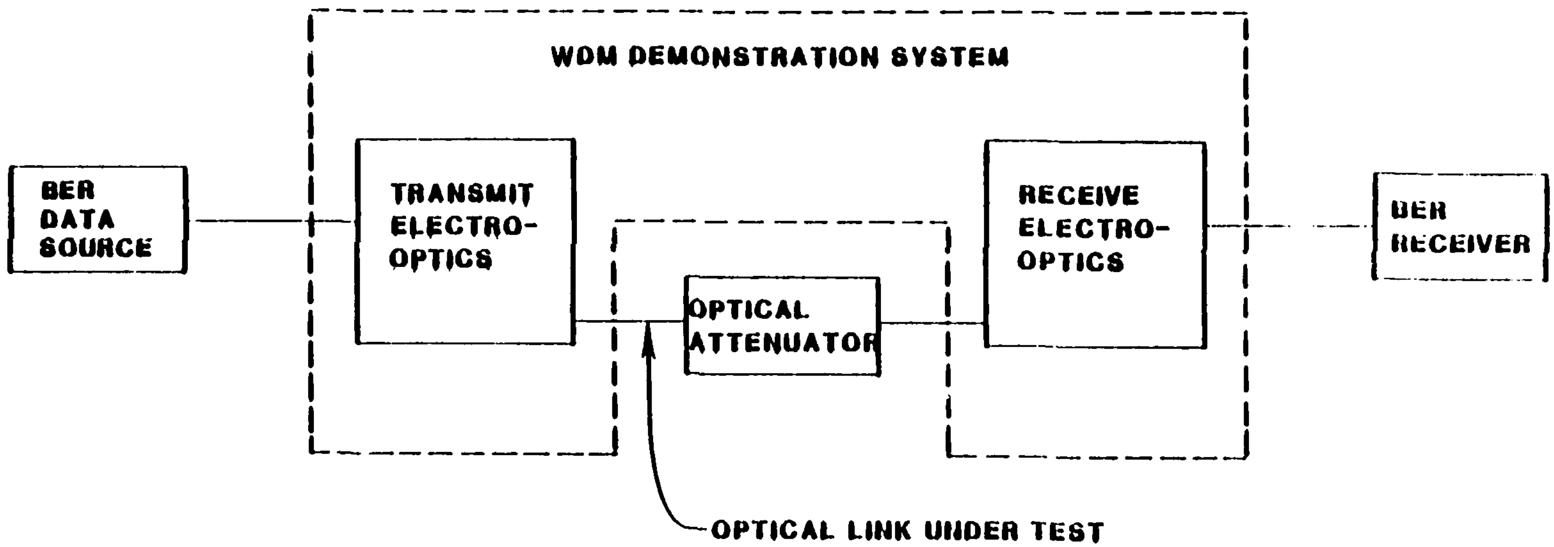


Figure 5.4.3-1. Optical Dynamic Range Tests.

23202

System RT is determined by the transmitter RT, the fiber RT, and the receiver RT. If these three values are known, the system RT may be calculated using:

$$(RT)_{system} = [(RT)^2_{transmitter} + (RT)^2_{fiber} + (RT)^2_{receiver}]^{1/2} \tag{5-2}$$

Direct measurement of the system RT can be made by injecting the transmitter with test pulses having much faster transition times than those of the system and then observing the transition times of the signal at the linear output of the receiver. These transition times will be the system rise and fall times. Verification that the test pulse transition times are much faster than the system transition times can be made by changing the test pulse slopes and monitoring receiver pulse slope changes.

5.4.5 Power Consumption

The power consumption of interest in this system measurement is due to the electrical circuit requirements of individual modules, not the total ac power drain. Consequently, test points are provided on the module circuit at the dc power supply. Power consumption is measured by use of a meter at these test points.

5.4.6 Skew

The system skew of both the transmitted clock signal and data is of interest. The AETMS parallel data interfaces are used to observe signal skew. With AETMS data or test data supplied at the parallel interface, the AETMS parallel output may be displayed on an oscilloscope on a bit-by-bit basis. The signal will be examined for deviations from the expected duty cycle.

6.0 CONCLUSIONS

The study results show that Air Force specified avionics information transfer systems can be implemented efficiently using WDM fiber optics. The use of WDM reduces the complexity of system electronics, reduces the number of fiber optic cable assemblies required, allows better use of the bandwidth available in optical fibers, and increases the redundancy possible in an avionics information transfer system. A four-channel WDM optical link over one fiber can easily support the communication needs of the high speed Airborne Electronic Terrain Map System (AETMS). A modular WDM system demonstrator was designed which can exercise the AETMS interface, the currently specified Air Force WDM systems (Appendix A), and future WDM systems.

System designs were made for three Air Force specified systems: a 4-channel bidirectional 100 Mb/s point-to-point link; an 8-channel 300 Mb/s point-to-point link; and a 4-channel, 32-terminal, 20 Mb/s data bus. The designs used components which are currently available or which will be available in the 1983-1985 time frame. A quantitative system analysis using OCAP showed that the WDM systems designed worked with good reliability margins. The OCAP analysis used detailed data from actual components to model system performance in terms of the key parameters - channel loss and crosstalk. The calculations to determine these parameters extended over a 300-nm to 1800-nm spectral region with 1-nm resolution and covered a dynamic range of up to 60 dB.

A critical assessment of available WDM components shows that the basic technology exists to build avionics WDM systems in the 1983 to 1985 time frame. The capabilities and performance of these systems, however, would be greatly enhanced if some development efforts were made on key components. These components, in rough order of their importance include, (a) highly selective diffraction grating couplers, (b) wavelength stable laser diodes, (c) high speed-high power light emitting diodes, (d) pin photodiode-FET receivers, and (e) low loss, low loss variation optical connectors. These specific component developments would have a major impact on the avionics fiber optics field.

7.0 RECOMMENDATIONS

The WPAFB/AFWAL Wavelength Division Multiplexing Study for Avionics Applications program showed, using quantitative system modeling, that avionic WDM fiber optic systems will work effectively with components expected to be available in the 1983 to 1985 time frame. Recommendations resulting from the program are in two areas: system hardware demonstration and key WDM component development. Hardware demonstration is the critical "next step" necessary on the path to actual aircraft use of WDM techniques. Key avionic WDM component development is necessary to ensure that "avionics qualifiable" components will be available for systems use. These two general recommendations are justified and detailed in the remainder of this report section.

Actual performance measurements on WDM avionic hardware are the only means by which the successful system operation predicted in the study just completed can be confirmed. It is recommended that the WDM demonstration system, designed during the study, be built in a configuration suitable for demonstrating the AETMS interface. Details of the components needed for this demonstration system, and the details of the AETMS WDM components themselves, are contained in the Level B1 Prime Item Development Specification produced during this study. If it is not possible to demonstrate the AETMS link because of high cost associated with the specialized electronics, the demonstration system should be built configured to at least run one or more of the Air Force base line system designs made under this study. Demonstration of these systems would fully verify the predictions of the current study and would confirm the general suitability of WDM for avionics information transfer.

Wavelength division multiplexing couplers, tightly specified laser diodes, high speed-high power light emitting diodes, pin-FET receivers, and optical fiber connectors were identified in the study as key components needing development. Advances in any one of these component areas could speed the implementation of avionic WDM links and would increase the performance of the links. Table 7.0-1 lists these areas and the essential reasons for which work in them is needed.

Wavelength division multiplexing fiber optic couplers are actually the key components which provide the capability of efficiently multiplexing optical signals onto a single fiber. The performance of these couplers determines to a large degree the system features feasible. Laboratory versions of the required couplers are under development, but the units being developed are not necessarily taking avionic systems into account. For example, many WDM couplers are being developed to operate in the 1200 nm to 1300 nm range. This range is a good spectral location for long range links but is unnecessarily expensive for aircraft use.

Table 7.0-1. Recommended Component Development for the 1983-1985 Time Frame.

Component	Goal	Impact
WDM couplers	High selectivity, 8 nm channel spacing Low temperature drift	Allow more WDM channels per link; reduce link crosstalk
Laser diodes	Central wavelength specified and stable within ±2 nm	More WDM channels possible, reliability problems associated with wavelength drift reduced
High speed, high power light emitting diodes	>200 MHz bandwidth with >100 μW coupled power to 50-μm/125-μm graded-index fiber	Eliminate many needs for laser diodes and consequently improve system reliability
pin-FET receivers	Performance within 3-4 dB of APD receiver designs	Eliminate need for avalanche photodiodes and consequently improve system reliability
Optical connectors	Avionics qualified with loss <1.0 dB ±0.2 dB	Permits modular cable installation on aircraft with reasonable impact on optical signal quality

High coupler selectivity and tight channel spacing can only be taken advantage of if stable optical sources for each channel are available. Laser diodes projected to be available in the 1983-1985 time frame will not have the desirable tight wavelength specifications unless some development specifically for WDM systems is done. Diodes are needed with emission wavelengths within several nanometers of the central channel wavelength. Furthermore, the emission wavelength must not significantly change during operation or aging of the diode. This is a serious problem which will perhaps require optical feedback loops sensitive to laser wavelength.

High-power, high-speed light emitting diodes, known to be under development for nonavionics uses, could benefit WDM systems by eliminating the need for lasers. Lasers might still be necessary for systems with very high (>50 dB) link losses, very high (>300 Mb/s) speeds, or very close (<10 nm) channel spacing. The more common WDM systems would use high performance light emitting diodes with highly selective couplers to control crosstalk. High LED output power would allow tight selection of channel wavelength by use of selective multiplexers. A key advantage of this approach is that multiplexer rather than source characteristics would determine overall WDM system performance and the sensitivity of the performance to evnironmental changes. Figure 7.0-1 illustrates this concept, which was actually suggested by the system sensitivity analysis of Air Force system II. Development of the

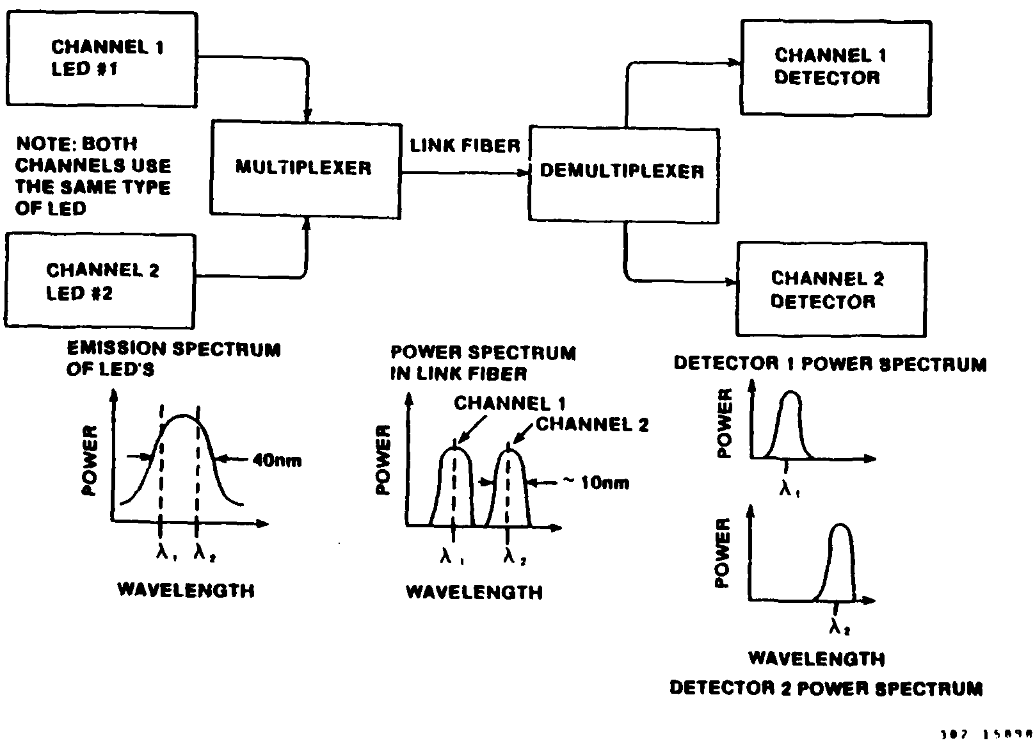


Figure 7.0-1. High Performance LED System Example.

light emitting diodes is needed along with further system analysis of the concept. Use of this technique could radically change the currently held ideas about WDM systems. Identical sources could even be used for several channels.

The pin-FET receivers have the promise of the performance of avalanche photodiode (APD) receivers without the drawbacks of the APD receiver. Avalanche photodiodes are sensitive to temperature, require high voltage bias, and are sensitive to radiation. The pin-field effect transistors do not have these serious problems and seem to be a very sound technique to use for avionics fiber optic receivers.

The final component identified for development is the optical connector. Currently available connectors have too great an insertion loss and too great a variation in insertion loss to allow flexible system design. The cumulative effect of current connector performance is to preclude the use of many connectors in a link and to require high dynamic range performance of the receivers. Development of a connector and tight fiber specifications are needed to solve these problems. Design of the connector could be similar to current units; the performance, however, must be better.

Overall consideration of the recommendations made in this report shows that there is interaction between several of the components which can be exploited in a constructive sense. This interaction has been identified in this WDM study because of insights provided by OCAP, the program developed and used during the study. The three components involved in this recommended synergetic development effort are (a) WDM couplers, (b) high-power, high-speed light emitting diodes, and (c) pin-FET receivers. The couplers would provide ~10 nm wide channels in at least the 800-nm to 900-nm spectral region. Light emitting diodes with spectral emission widths sufficient to cover about three channels per device would be developed. The pin-FET receivers for at least the 800-nm to 900-nm region would be developed. The combination of these components would produce avionic WDM systems which eliminate many of the problems identified in the study presented in this report.

8.0 REFERENCES

1. Anderson, G. "Study of Cabled Fiber Performance as a Function of Temperature," ITT Internal Report.

2. Johnston, A. R., and L. A. Bergman. "Applications of Fiber Optics in Spacecraft," Fiber Optics for Communications and Control, SPIE (Vol 224) (1980).

3. Yeung, W. F., and A. R. Johnston. "Effect of Temperature on Optical Fiber Transmission," Applied Optics, (17) (23) (Dec 1, 1978).

4. Epworth, R. E. "The Temporal Coherence of Various Semiconductor Light Sources Used in Optical Fibre Sensors," presented at the Conference on Fibre Optic Rotation Sensors and Related Technologies, Massachusetts Institute of Technology (Nov 9-11, 1981).

5. Epworth, R. E. "The Measurement of Static and Dynamic Coherence Phenomena Using a Michelson Interferometer," presented at the Fifth European Conference on Optical Communication, Amsterdam (September 1979).

6. Epworth, R. E. "The Phenomenon of Modal Noise in Analogue and Digital Optical Fibre Systems," presented at the Fourth European Conference on Optical Communication, Genoa (September 1978).

7. Vidula, B. S. "Time Division Multiplexing Techniques Assessment," ITT report produced under contract to Rome Air Development Center.

APPENDIX A

STATEMENT OF WORK

SECTION C

DESCRIPTION/SPECIFICATIONS

DATE 80 Dec 01

A Study of Wavelength Division Multiplexing for Avionics Applications

1.0 INTRODUCTION

1.1 TECHNOLOGY BASE:

Until recent advances in narrow spectral width sources, wavelength (color) division multiplexing (achieving many parallel data channels on a single fiber) was considered impractical. An additional factor which limited practicality was the relatively poor stability of the peak wavelength of the source versus temperature. Typical values for spectral width and wavelength drift for LEDs were 40nm and 0.13nm/^{o}C respectively. Today's laser source technology offers spectral widths of $\pm$0.1nm and wavelength temperature dependence on the order of 0.05nm/^{o}C.

Early studies of wavelength division multiplexing showed that application was also inhibited by lack of an acceptable methodology for separating the various channels at the receiving terminals. Approaches included bandpass filters either of the absorptive or dielectric (nonabsorbing) interference type, and dichroic filters. Typical deficiencies of these approaches were poor environmental stability, inadequately narrow bandwidth, angle-of-incidence dependence, and implementation difficulty. An alternate receiver design consideration was the development of wavelength matched photodiodes of GaAlAs; however, this technology is still in its infancy and has its own set of implementation complexities. Recently reported mux/demux techniques (ref. 3.4.d) with much improved performance characteristics, viz. grating devices and those incorporating graded refractive index (GRIN) lenses, coupled with new source technology provide the capability of multiple wavelength division multiplexing within the maximum spectral sensitivity range of existing, well established silicon type photodiodes. An activity is appropriate, at this time, to study the state-of-the-art, to investigate system implementation techniques and trade-offs, and to provide direction for the further development of wavelength division multiplexing technology for military avionics.

2.0 SCOPE

2.1 PROGRAM OBJECTIVES: The primary objective of this study and analysis effort is to establish wavelength division multiplex (WDM) technology baseline design(s) which can be used to satisfy current Avionics Information Transfer requirements and is extendable for use in future applications. Specifically, under this program the technology will be thoroughly investigated for its applicability to avionics systems through sensitivity type analyses (ref. 4.3). These analyses will be performed on system topologies and system data transfer requirements (specified by the Air Force) which are representative of Air Force avionics applications and at the same time permit the full investigation of the technology.

2.2 STATEMENT OF WORK SUMMARY: This statement of work defines the total effort to be provided by the contractor over a 12 month period (9 months technical effort). The program involves:

a. Design of several WDM information transfer systems.

b. Sensitivity analysis of various WDM systems implementations and performance characteristics.

c. Technology forecast for identifying anticipated new technological opportunities at both the systems and components levels.

d. Derivation of a WDM demonstration system design.

e. Documentation.

2.3 PROGRAM OUTPUTS: The primary aim of this effort is to develop an understanding of the baseline attributes and capabilities of WDM technology from the process for rational selection of system components to detailed analysis of system performance. Thus, an important output of this program shall be the concise documentation for further Air Force use. To provide for a more thorough understanding of the "workings" of the technology, hands-on experience is planned for in a following hardware development contract. The definition and documentation of a relevant WDM system demonstrator to support this follow-on will be a key output of this program. In anticipation of a continuing Research and Development program is this technology area, the required technology forcast output from this effort is designed to support projection of its capabilities into the 1985 timeperiod and provide the basis for an Air Force long range (3-5 yr) development plan is this area. Component development and hardware development are not within the scope of this contract.

3.0 GENERAL BACKGROUND

3.1 PROGRAM EVALUATION: The potential advantages of wavelength division multiplex data transfer techniques have been recognized since the inception of fiber optics technology. Particularly attractive is the capability of full duplex operation and use of a common bus for both digital and analog transmission. However, for military aircraft applications there have existed two major milestones to be achieved before serious consideration could be given to its use. First, and foremost, was overcoming the deficiencies associated with the immaturity of the state-of-the-art. These included performance limitations associated with existing components and non-existence of other critical elements. Secondly, development of the technology for purely technological reasons was insufficient justification to gather program support. That is, a clear systems need for the enhanced capabilities offered by wavelength division multiplexing was not identified.

3.2 REQUIRED TECHNOLOGY: Recent advances have brought about the required maturity of the technology. This is particularly true in the areas of tunable, stable sources and wavelength mux/demux devices of the desired wavelength characteristics and quality factors. Developments which contributed to these advances were primarily improved and expanded materials technology and the subsequent capability to investigate and develop innovative device structures and configurations.

SECTION C

DESCRIPTION/SPECIFICATIONS

DATE 80 Dec 01

3.3 APPLICATION: Studies of A.F. electronic warfare (EW) systems such as the Advanced Power Management System (APMS)(ref. 3.4b), COMPASS TIE (ref 3.4e,f) and the EF-111A (ref 3.4b) have shown that sufficient benefit is derived to justify system redesign for fiber optics if it's wideband/high data rate capability is coupled with wavelength division mux techniques. These results are a consequence of the characteristics of typical EW systems: multiple parallel data channels and high composite data rates. For example, a study of the interface between the High Probability of Intercept Receiver (HPIR) and Electronic Support Measures (ESM) in the APMS has shown that through the use of wavelength division mux techniques the system interconnect scheme can be significantly simplified and system performance can be improved in terms of subsystem separation distance and flexibility for future growth.

For general avionics applications state-of-the-art WDM offers numerous design options. With the trend towards avionics systems with distributed processing elements and the associated requirement for "real-time" processor interfaces, WDM provides an attractive option to routing 16-parallel line processor busses throughout the aircraft. New avionics systems have also been projected to require 10's of Megahertz busses to satisfy increases in system performance and new architectures (hierarchical) under consideration. Of primary concern at these higher bus rates is the decrease in bus efficiency due to "bus overhead" factors. One can envision the utilization of WDM to releive this concern by utilizing one wavelength for transmission of data ~~only~~ and a second wavelength for transmission of conventional "bus overhead" information over the same single fiber.

3.4 REFERENCE DOCUMENTS: Documents applicable to this effort are listed below:

a. ONR-NR215-166, "Wavelength Division Multiplexing in Light Interface Technology", IBM, 19 March 1971.

b. AFAL-TR-79-1165, "EW Applications of Fiber Optics", Dalmo-Victor/Lockheed, August 1979.

c. CORADCOM, 771798-F, "Bi-Directional Coupler for Full Duplex Transmission on a Single Fiber", ITT, August 1979.

d. Optical Communication Conference Proceedings, Amsterdam, 17-19 September 1979.

e. AFAL-TR-70-1094, "F-16 Internal Electronic Countermeasures/COMPASS TIE and Electronic Warfare Fiber Optic Data Bus (u), "Sanders (Confidential), July 1979.

f. AFAL-TR-79-1095, "Lightweight Low-Cost ECM, Phase III, Vol. II, F-16 IECM/COMPASS TIE Interface with F.O.", ITT, September 1979.

4.0 TECHNICAL REQUIREMENTS/TASKS

4.1 OVERVIEW: The contractor shall conduct a design and analysis program to establish wavelength division multiplex technology baseline designs which satisfy the information transfer requirements and system topologies specified herein. Sensitivity analyses shall be performed on the systems to establish a performance range for each design using existing componentry. In addition to deriving designs which satisfy specified system requirements, the contractor shall take into consideration, during the design process, the requirement to ultimately operate in an avionics environment of -54°C to +95°C (Ref. MIL-E-5400R, class II). Also, a technology forecast shall be performed to identify new technological opportunities both at the components and systems level. Although no hardware is to be built under this program, the contractor shall prepare a WDM system development specification including provisions for demonstration and evaluation of system capabilities.

4.2 CONCEPTUAL SYSTEMS DESIGN: The contractor shall develop a design for each of the three systems specified in paragraphs 4.2.1, 4.2.2 and 4.2.3. The designs shall be constrained to the use of available technology and shall be in sufficient detail to: (1) support the required analyses described in paragraph 4.3 and (2) permit the Air Force to assess the practicality of realizing a working system in a follow-on development program. Designs, with supporting rationale, shall be submitted to the Air Force (Ref. CDRL Seq No. 7) and approval received prior to proceeding with the analyses. In particular, the supporting rationale shall describe the process for selection of components and WDM system implementations, and for determination of performance characteristics. Also, the rationale shall describe the contractor's step-by-step, iterative procedure for deriving designs for the specified WDM systems. (Refer to Attachment 1 for topological descriptions and guidelines for the systems to be designed).

4.2.1 Air Force Selected Parameters (System I)

a. Multi-Channel, point-to-point link

b. Duplex

c. Protocol: One to n emitters transmitting at any one time

d. Digital Data Rate (DR): DR $\geq$ 100 Mbps per channel

e. Number of Wavelengths (n): $n \geq 4$

4.2.2 Air Force Selected Parameters (System II)

a. Multi-Channel, point-to-point link

b. Simplex (Unidirectional)

c. Protocol: One to n emitters transmitting at any one time

d. Digital Data Rate (DR): DR $\geq$ 300 Mbps per channel

e. Number of Wavelengths (n): $n \geq 8$

4.2.3 Air Force Selected Parameters (System III)

a. Multiterminal Data Bus

b. Protocol: One to n emitters transmitting at any one time

c. Number of Terminals (m): $3 \leq m \leq 32$

d. Number of Wavelengths (n): $2 \leq n \leq 8$

e. Digital Data Rate (DR): 1Mbps $\leq$ DR $\leq$ 20Mbps per channel

4.3 SYSTEM SENSITIVITY ANALYSES: The contractor shall thoroughly investigate the performance of the approved designs in conjunction with sensitivity analysis techniques. For the purposes of this program "sensitivity analysis" will be defined as the process of quantifying the relationship between a change in input and a change in output variables, identification of the magnitude and rate of change between variables and delineation of critical parameters (i.e., those with the greatest impact on system performance). Through these analyses the performance of fiber optic system components, their interrelationships, and the impact of key parameters on the capability of satisfying system performance requirements shall be investigated. The analysis variables shall be parameters such as the number of system inputs (and outputs), input/output optical power levels, channel separation, dynamic range, signal structure/formats, noise levels, and data rates. System performance parameters such as crosstalk, signal-to-noise ratios, and bit error rate shall then be used to characterize the systems. Any required additional analysis variables and system parameters to be used in the analyses shall be selected by the contractor and submitted to the Air Force for review and approval (Ref. CDRL Seq No. 8). Selection rationale of any additional variables and parameters shall be included as part of the above mentioned submittal and shall describe the relevance of each to a more complete understanding of the technology and system performance. In addition to reporting analyses results, constraints imposed on system performance by component limitations shall be identified and discussed.

4.4 TECHNOLOGY FORECAST: The contractor shall identify component developments which could provide for improved/expanded capability in the 1982-85 timeframe. The development of each item shall be appropriately prioritized and assigned a risk factor. Enhanced component capabilities shall be folded into the baseline designs for the purpose of extrapolating additional system capabilities thus made available. This will provide the Air Force with the data necessary to decide whether component development is warranted to support a future update of WDM system capabilities. Identified component developments shall be completely described. For example the description for source development, if applicable, shall include the following parameters (with recommended values): (1) optical power, (2) wavelength, (3) spectral width, (4) wavelength and amplitude stability with temperature, (5) operating current and temperature, (6) optical apertures and mode structure, (7) mode stability, (8) speed of response and (9) linearity. Considerations which do not necessarily affect the above parameters such as ease of manufacture, packaging, lifetime and rate of degradation with time shall also be included. Descriptions of similar detail shall be prepared for all components identified as requiring development.

4.5 DEMONSTRATION SYSTEM DESIGN: The contractor shall develop and submit for Air Force review and approval (Ref. CDRL Seq No. 9) a design for a Wavelength Division Multiplex demonstration system which is both compatible with the interface described below (ref. paragraph 4.5.1) and capable of serving as a general purpose demonstrator through appropriate software and/or hardware modifications (ref. paragraph 4.5.2).

4.5.1 WDM SYSTEM DESIGN: The contractor shall develop a design for the fiber optics portion of the demonstration system (i.e., all elements between the fiber optics transmitters and receivers, inclusive) and any ancillary electronics required to interface the WDM system to the Air Force selected equipment interface. Specifically, the subject Air Force selected interface is one of many within the "Airborne Electronic Terrain Map System" (AETMS) currently being developed under Avionics Laboratory sponsorship. Functionally, this interface is comprised of 3 channels, each of which is 16 lines wide for 16-bit parallel data transfer, and 1 channel 8 lines wide accommodating a 8-bit parallel data transfer requirement. Each of the 56 lines are designed to operate at 1.5 Mbps with a design growth option for operation at 3.0 Mbps. For the purposes of the demonstrator the WDM design shall be optimized for the 3.0 Mbps data rate on each of 56 parallel lines and operable at 1.5 and 3.0 Mbps. Thus the contractor shall be responsible for design of the electronic multiplex and demultiplex electronics required for formatting the data for WDM transmission and recovery. One obvious possibility, for example, would be to electronically multiplex each of the 16-bit channels onto one (> 48Mbps) serial line each, the 8 bit parallel channel onto (>24 Mbps) serial line, and transmission over a four wavelength multi-channel, point-to-point system. The more detailed specifics (e.g. timing, jitter, skew, delay, voltage levels, etc.) of the selected AETMS interface required for the WDM demonstrator design will be provided by the Air Force. (As a part of the follow-on development program, an Air Force/Contractor Interface Working Group will be established and given responsibility for developing and coordinating a detailed Interface Control Document which will assure proper integration of the WDM and AETMS Systems.)

4.5.2 WDM PROGRAMMABLE CONTROLLER DESIGN: The programmable controller shall be capable of exercising the system in various operating modes and monitoring critical system and component performance characteristics. A required feature of the design shall be the flexibility to switch from the AETMS mode of operation to one which allows the Air Force to pass compatible data signals through the WDM system. Thus, an appropriate switching function and input/output ports shall be provided for each wavelength channel and located before/after the fiber optics transmitter/receiver electronics, respectively. Other modes of operation which are to be provided include, but are not limited to, continuous and independent drive current control of individual (optical) sources, digital pulse conversion (i.e., accepting and buffering some externally provided lower data rate digital signal for transmission at the higher (AETMS) WDM designed rate and reconstruction of the lower rate signal at the receiver), pulse train generation (for example in MIL-STD-1553 format as well as random word), and other capabilities which contribute to the requirement for development of a general purpose information transfer demonstrator. In addition to providing for exercising/driving the WDM system, the controller shall also be capable of monitoring and/or displaying various system figures of merit which allow for quantifying of digital data transfer performance. System performance parameters such as bit error rate, link delay, optical dynamic range, power consumption, signal risetime and falltime (electrical and optical skew, and others, shall be considered primary candidates for measurement and display.

4.6 DEVELOPMENT SPECIFICATION: The contractor shall prepare and submit (Ref. CDRL Seq No. 10) a Wavelength Division Multiplex Fiber Optics System Development Specification of similar detail and content as a type B-1 Development Specification (Ref. MIL-STD-490). The build-to specification is intended to be used by the government as the basic document in an anticipated follow-on hardware demonstration program. The specification shall include a detailed parametric description of the WDM components.

5.0 REVIEWS: As a minimum, the contractor shall convene, at Wright-Patterson AFB, Ohio the program reviews as specified in the technical schedule. Attendees shall include selected contractor's personnel and representatives of the government. The contractor shall provide the Avionics Laboratory with supporting documentation (Ref. CDRL Seq. No. 3).

6.0 GOVERNMENT FURNISHED DOCUMENTS

6.1 The contractor shall be responsible for independently acquiring all information to perform the requirements of the Statement of Work except as provided in paragraphs 6.2 and 6.3.

6.2 Documentation delineated in paragraph 3.4 will be provided on temporary loan by the Avionics Laboratory for review if specifically requested by the contractor.

6.3 The detailed specifics of the selected AETMS interface (ref. paragraph 4.5.1) required for the WDM demonstrator design will be provided by the Air Force.

7.0 REPORTS, DATA AND OTHER DELIVERABLES: The contractor shall prepare and deliver all data documents listed on the Contract Data Requirements List (CDRL, DD Form 1423).

PR NO. FY11758100432

Attachment I

to the Statement of Work

System Requirements Selection Rationale

and

WDM System Design Guide

1.0 Introduction: The basic guideline used in development of this effort was the desire to analyze wavelength division multiplexing from a bottom-up technology view point in determining its applicability to avionics information transfer and it's contribution to the goals of the System Avionics Division of the Avionics Laboratory. The selected WDM system configurations and data transfer requirements specified in paragraphs 4.2.1, 4.2.2 and 4.2.3 of the SOW, and repeated below, allow for the full investigation of the technology as a function of topologies and data transfer needs representative of Air Force avionics systems.

1.1 Air Force Selected Parameters (System I):

a. Multi-Channel, point-to-point link
b. Duplex
c. Protocol: One to n emitters transmitting at any one time
d. Digital Data Rate (DR): DR $\geq$ 100 Mbps per channel
e. Number of Wavelengths (n): $n \geq 4$

1.2 Air Force Selected Parameters (System II):

a. Multi-Channel, point-to-point link
b. Simplex (Unidirectional)
c. Protocol: One to n emitters transmitting at any one time
d. Digital Data Rate (DR): DR $\geq$ 300 Mbps per channel
e. Number of Wavelengths (n): $n \geq 8$

1.3 Air Force Selected Parameters (System III):

a. Multiterminal Data Bus
b. Protocol: One to n emitters transmitting at any one time
c. Number of Terminals (m): $3 \leq m \leq 32$
d. Number of Wavelengths (n): $2 \leq n \leq 8$
e. Digital Data Rate (DR): 1Mbps $\leq$ DR $\leq$ 20Mbps per channel

2.0 System Requirements Rationale: The rationale used by the Air Force in deriving the specified requirements is as follows.

F33615-81-R-1481

2.1 Air Force Selected Parameters (System I): From an applications viewpoint multi-channel point-to-point links currently represent a major category of data transfer system configurations on aircraft. The requirement for duplex operation is characteristic of numerous aircraft applications which require command acknowledgement. Specific avionics requirements which fall within this application category are well documented in ref. 3.4 (b) of the work statement. Of the many applications which could be addressed, parallel data transfer at high composite data rates is an area which is well suited to the projected capabilities of WDM. From a technology consideration multi-channel point-to-point configurations represent a first logical starting point to investigate WDM in terms of complexity and risk. System I, in addition, will address the requirement for WDM full-duplex operation. This approach will require the contractor to address critical issues, such as full duplex channel-to-channel coupling which require analyses for a full understanding of the technology. The specification for number of wavelengths, starting at the low end of four, forces consideration of LED's as optical sources, since they are currently the least costly and most reliable. This, coupled with the 100 Mbps requirement, which is a reasonable state-of-the-art data rate for low bit error rate operation using LEDs, provides the vehicle for investigating LED/Wavelength Division Multiplex capabilities. The objective for analyzing system performance as a function of data rate and number of wavelengths is as follows. At some performance level a transition will occur where laser devices become required. Studies of this parameter will establish the boundary beyond which a LED approach is not appropriate. Finally, the analysis of this system will consider a number of channel separation (wavelength multiplex and demultiplex device) schemes and specify appropriate avionics application ranges for each.

2.2 Air Force Selected Parameters (System II): The selections for performance for System II were largely derived as a complement to System I. The initial specification for eight wavelengths forces consideration of laser diode devices and the various complexities of stable, reliable, controllable laser operation. The 300 Mbps per channel also forces the laser issue and is a data rate that could accommodate, for example, high quality digitized video type information. It is envisioned that a number of vital trade-offs will evolve from analysis of this system. For example, a channel density limit will be reached beyond which operation in the 8.0μm to 0.9μm wavelength regime becomes impractical. Analyses should provide trade-offs, for example, between data transfer over a single WDM link which includes wavelengths beyond 0.9μm, vs. remaining within the 0.8– 0.9μm regime and performing the data transfer function over two or more WDM links having fewer wavelengths each. Implied in this trade-off would be selection of mux/demux devices as well as other system considerations.

2.3 <u>Air Force Selected Parameters (System III)</u>: One of the primary technologies currently under consideration for satisfying the requirements of advanced hierarchical data bus architectures is fiber optics. The motivation for this consideration is the ease with which fiber optics can accommodate bus rates grater than 1 Mbps. The added option of wavelength division multiplixing for such busses has the potential of opening an entire new range of bus architectures and protocols. For example, to reduce bus overhead burden one wavelength, λ1, could be used for transfer of data only and a second, λ2, for bus control. Thus, at the same time data transfer is occurring, the setting-up of the next data transfer activity occurs on the same single fiber bus, increasing bus efficiency. Further, given the trend in distributed and shared processing, and requirement to access any processor's memory for "dump" in case of failure, a third wavelength, λ3, could be devoted to that function and coupled to the same bus with no impact on the performance of the other functions (data and control). Other data transfer opportunities such as these will become apparent as the technology is further investigated. The detailed WDM parameters for System III were judiciously selected. First, they provide the vehicle for investigation of the lower end of the data rate spectrum, which includes the anticipated data rate range for near term advanced bussing systems. Also, they allow for a maximum analysis cross-coupling to occur across all three systems relative to selection of optical sources and multiplex and demultiplex techniques, thus somewhat limiting the amount of analysis required. It is envisioned that given the analysis of Systems I, II, and III the performance of practically any other data transfer application of interest can be extrapolated (e.g., high rate busses of many wavelengths).

3.0 System Design Guide.

3.1 System I, II and III: The baseline designs for Systems I, II and III should generally be tailored to meet the specified requirements in terms of data rate and number of wavelengths. However, the contractor should be prepared to make minor modifications to these baseline designs if initial analysis indicates that significantly increased knowledge can be obtained through analysis of systems of slightly greater capability. This is expected to be the case for System III where, for example, a baseline design of 8 terminals/2 wavelengths/10 Mbps data rate offers greater analysis flexibility than a baseline of 3 terminals/2 wavelengths/1 Mbps data rate. Obviously, other parameters besides data rate and wavelength are pertinent for an initial description of a baseline system and will have to be assumed. For example, initial assumptions will have to be made for such parameters as channel isolation. Assumptions and the justification for the values chosen for all baseline system design parameters should be stated clearly and discussed. Baseline designs should be derived keeping in mind that, from a systems viewpoint, establishing system growth capability and channel capacity are among the key interests of the Air Force.

3.2 WDM AETMS System Design: The design of the WDM system to satisfy the AETMS function shall exploit as many key features of the technology as possible. For example, although only 4 wavelengths may be required for the AETMS interface, utilization of an 8 wavelength multiplexer and demultiplexer would add significantly to the utility of the demonstrator. Similarly, incorporating two LEDs and two laser diodes would provide a broader data base then four sources of the same type. These and other demonstration system considerations should be direct derivatives of analysis results, and included as part of the initial submission of the demonstrator design (Ref. paragraph 4.5 of the SOW).

APPENDIX B

INDUSTRY SURVEY RESPONSE TABLES

WDM Manufacturers Contacted

American Holographic

Gandalf Data

Hughes

NEC Electronics

Optelecom

Phalo OSD

Raytheon, Data Systems

Times Fiber Communications

Valtec, Fiber Optics

Harris

TRW

Canstar

Opto Electronics

Fibronics

Kaptron

ATTACHMENT B

Vendor Surveys

<u>Sources - 0.8 to 0.9 μm, 1.2 to 1.3 μm</u>

Manufacturers with devices in desired range

AEG - Telefunken

Amperex - Slatersville

Anritsu

Fujitsu

GE - Semiconductor

General Optronics

Hitachi

Laser Diode Labs (now Miacon Laser Diode)

Lasertron

Mitsubishi

Motorola

NEC

Plessey

Optical Information Systems

Opto - Diode

RCA

<u>Detectors</u>

Manufacturers contacted

InGaAs(P)
- Lasertron
- Mitsubishi
- Plessey

Germanium
- Ford Aerospace
- Judson
- Math Associates
- NEC
- Photon Kinetics
- Rofin

Silicon pin
- AEG - Telefunken
- Centronic
- Codenoll
- EG & G Electro-Optics
- Ford Aerospace
- Hewlett - Packard
- Math Associates
- Motorola
- NEC

ATTACHMENT B (continued)

Detectors (continued)

- RCA
- Siemens
- TRW-Optron
- Texas Instruments

Silicon APD

- Centronic
- Mitsubishi
- NEC
- RCA
- Texas Instruments

LASER DIODE VENDOR SURVEY

800-900 nm, 1.2 - 1.3 μm

LASER DIODE VENDOR SURVEY

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (mW)	Cost	Other
Mitsubish:								
ML-2000	min-795 typ-830 max-905	-55 to 100/ -40 to 50	~0.1	30	-	6	-	$\frac{\Delta\lambda}{\Delta\tau}$ = 0.2 nm/°C
ML-7205	1300 ± 30	-20 to 70/ -20 to 50	~0.1	25	-	6	-	InGaAsP/InP buried cresent lasers
ML-4001	780 + 20	-55 to 100/ -40 to 50	~0.1	30	-	6	-	pin monitor photodiode $\frac{\Delta\lambda}{\Delta\tau}$ = 0.2 nm/°C
ML-3001	min-795 typ-830 max-905	-55 to 100/ -40 to 50	~0.1	30	-	6	-	pin monitor photodiode $\frac{\Delta\lambda}{\Delta\tau}$ = 0.2 nm/°C
ML-5308	min-795 typ-830 max-905	-55 to 100/ -40 to 40	-	35	-	15	-	-
ML-4101 4401	780 + 20	-55 to 100/ -40 to 40	~0.1	30	-	6	-	pin monitor photodiode $\frac{\Delta\lambda}{\Delta\tau}$ = 0.2 nm/°C
ML-5101 5401	min-795 type-830 max-905	-55 to 100/ -40 to 40	~0.1	25	-	30	-	pin monitor

LASER DIODE VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (mW)	Cost	Other
Hitachi:								
HLP 5400	1300 ±30	0 to 60/ 0 to 50	0.25	30	0.5	0.7	-	-
HLP 5600	1300 ±30	-40 to 60/	0.25	30	0.5	3	-	-
HLP 5700	1300 ±30		0.25	30	0.5	3	-	-
HLP 5500	1300 ±30	-40 to 50	0.25	30	0.5	3	-	pigtailed 50/125 - 0.2 NA, GI, ~50 cm
Laser Diode Labs:								
LCW-10	830*	-55 to 125/ 0 to 60	2.5	90	100 ps	0.7 c-2	-	*Wavelength ranges available (nm) A 800 to 890 B 810 to 840 C 840 to 860 D 860 to 880
SCW-20	830*	-55 to 125/ 0 to 60	1	50	100 ps	7	-	*Same λ ranges as above
LA-60	840		3.5	2.5	1	1.5 W	-	*Same λ ranges as LCW-10
LA-63	840	-196 to 150/	3.5	4	1	5 W		
LA-65	840	-196 to 75	-	7	-	-		
LA-68	840		-	12	-			

---

*c-coupled

LASER DIODE VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (mW)	Cost	Other
Laser Diode Labs (continued):								
LD-60	904		3.5	3 A		2.3 W	-	*Same λ range as LCW-10
LD-61	904		3.5	3.5 A		1.5 W	-	
LD-62	904		3.5	6 A		6 W	-	
LD-63	904	-196 to 150/	3.5	7 A		6 W	-	
LD-64	904	-196 to 75	3.5	10 A	<0.5	12 W	-	
LD-65	904		3.5	12 A		9.5 W	-	
LD-66	904		3.5	16 A		20 W	-	
LD-67	904		3.5	18 A		20 W	-	
LD-68	904		3.5	18 A		20 W	-	
QP-123	1.04 <λ* λ <1.4	-	5	1 A	1	75	-	*λ from 1.4-1.6 μm available with special order Fibered lasers available
QCW-123	1100 <λ <1350	max 50°C	5	200	250 ps	6	-	Fibered available

LASER DIODE VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (mW)	Cost	Other
Lasertron:								
QLM-1300	1300 ±30	max 70°C	Single-mode 1 mm-5	100	-	c-4 single-mode c-3 7	-	InGaAs monitor detector. Thermo-electric cooler may be customized for particular fiber optic pigtail; center λ may be specified. Also available in package for developmental applications with or without monitor detector
AEG Telefunken:								
CQL121 V294P	850 ±5	-55 to 60	2.5	100	~3	2000	CQL12 $800 V294P $725	CQL12 has control diode; lifetime ~1 mill hrs. λ may be adjusted to customer specification. Available in steps of 10 nm from 780 bandwidth-350 MHz

*c-coupled.

LASER DIODE VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (mW)	Cost	Other
Fujitsu:								
FLD13D Series	1300	-50 to 70/ -40 to 50 coupled - -40 to 40	2	20	0.5	5	-	Available pigtailed monitor optical output or optical current
FLD074	780 ±20	-55 to 125/ -40 to 60	1	30	1	5	-	Mates with pin photodiode for monitoring single-mode
General Optronic:								
GOLS- (<1000)	825 ±45	-55 to +100/ -40 to 70	.3-1.3	60-100	0.7	7	-	Multimode - GaAs/ GaAlAs
GOLS- 1300	1300 ±50	-40 to 70/ -55 to 100	.9-4.5	100-155	0.7	5-7	-	InP/InGaAsP
GOLS- 500	825 ±45	-40 to 70/ -55 to 100	<.01	20-60	0.7	20-30	$2000	GaAs/GaAlAs single-mode
GOLS- 4000	835 ±35	-40 to 70/ -55 to 100	<.01	30-100	<1	20-30	-	GaAs/GaAlAs "high power"

LASER DIODE VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (mW)	Cost	Other
General Optronic (continued):								
GO-DIP	820 ±10	-50 to 80/ -40 to 65	.84 ±.46	90-110	<1	3	-	Pigtailed - 50/125 .02 NA - customer may supply other pigtail fiber with monitor available with optional themoelectric cooler. This option allows for a 45°C differential between laser and case $\frac{\Delta\lambda}{\Delta t}$ = .2 nm/ °C
GO-DIP 1300	1300 ±25	-50 to 80/ -40 to 55	3.6 ±.09	120	1	2	$3250	Wavelengths outside this range are available. Single-mode and single-mode fiber pigtails are available same as above GO-DIP
RCA:								
C86006E C86007E	820	-196 to 125/ - 35 to 50	4	250	<1	86007-6 86006-3	-	Internally coupled cable

LASER DIODE VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (mW)	Cost	Other
RCA (continued):								
C86000E	820	-55 to 125/ -35 to 50	2	75	<1	10	-	
C86022E C86023E	1300	-55 to 60/ -35 to 50	5	150	<1	86022E-1 86023E-7	-	86022 - internally coupled cable
NEC:								
NDL3108	850	Operating -40 to 70 S-40 to 70 P-20 to 60 Storage -55 to 125 S-55 to 125 P-20 to 60	1.5	105	.5	*15 P-3.5 S-10	$315 $530	*Packages available = glass window To-5 S-selfoc P-pigtail $\frac{\Delta\lambda}{\Delta t} = .2$ nm/°C
NDL3205	850	-55 to 125 S-40 to 70 P-20 to 60/ -40 to 70 S-20 to 60 P-20 to 60	1	65	.5	*8 S-5 P-2.5	$445 -$655	Single-mode P-pigtail S-selfoc $\frac{\Delta\lambda}{\Delta\tau} = \frac{.2nm}{°C}$

LASER DIODE VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (mW)	Cost	Other
Opto-Electronics:								
PLS-10	*See other	–	–	–	–	–	λ range 1, 2 $2800 1100-1350 $7300	*Wavelength ranges (1) 810-870 (2) 900 (3) 1100-1600 Tolerances (1) ±10 nm (2) ±10 nm (3) ±50 nm

LED VENDOR SURVEY

800-900 nm, 1.2-1.3 μ

LED VENDOR SURVEY

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power C-coupled	Other
Opto Diode:							
OD 820C	820	-	50	100	20	3	-
OD 880 Series	880	-	80	100	0.5	20	-
Plessy:							
HR1301	1300 ±50	-65 to 125/ -40 to 90	90	150	3	C-50/125/ NA = 0.2 50 μW	Bandwidth - 80 MHz $900
HR810	850 ±30	-65 to 125/ -40 to 90	40	200	3	C-50 μ/0.2 NA/ GI-150 μW 100 μ/0.3 NA/ SI-750 μW	"Wide bandwidth" lifetime - >1 mill hrs; military standard
RCA:							
S86017 86018 86020 86021	820 ±30	-40 to 120/ -40 to 90	50	200	86017, 86020 8 ns 86018, 86021 3 ns	86017, 86020 continuous- 150 μW Pulsed-3.5 mW 86018, 86021 continuous- 1250 μW pulsed-6 mW	Bandwidth 50 MHz - 017,020 150 MHz - 018, 021
C86013E	1300	-40 to 60/ -35 to 50	60	200	<10	C-50 μW	-
C30133	820 ±20	-40 to 75/ -40 to 75	60	1 A	3	0.5	Bandwidth 150 MHz

LED VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (C-coupled)	Cost	Other
Motorola:								
MFOE106F	820	-30 to 100/ -30 to 85	35	150	20 ns- max 15 ns- typical	900 μW		
MFOE107F	812 nm	35	200	15 ns	15 ns	1100 μW, 1500 μW		
NEC:								
NDL4103A	850	-55 to 125/ -30 to 80	40	100	10 ns	2 μW		
		COUPLED -30 to 80/ -30 to 80				C-50/ 125/ NA=.2 .05 μW		
Laser Diode Labs:								
IRE-160	820 nm ±15	-40 to 85/ -40 to 85	40	100 mA	15 ns	300 μW C-125/ 200 NA=.3 250 μW 50/125 .2 NA- 60 μW	$97 c-$225	Bandwidth 40 mbs

LED VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power C-coupled	Cost	Other
IRE-161	820 ±15	-40 to 85/ -40 to 85	40	100 mA		C-50 μm/- 2 NA- 50 μW 125 μm/- 3 NA- 200 μW 250 μm/- 3 NA- 600 μW	$68	Bandwidth - 40 mbs $\frac{\Delta\lambda}{\Delta t} = 2\mathring{A}/°K$
DE-1000	1270	-10 to 60/ -10 to 60	100	100 mA	5 ns	C-50/ 125- .2 NA 20 μW		
IRE-151	820 nm	120/50	35	200	8 ns	800 μW	$54 $165-C	Coupling efficiency 25%
IRE-150	820 nm	150/50	35	150	7 ns	1.5 mW	$62.70 $165-C	Coupling efficiency 25%
Lasertron:								
QLED-1300	±30 nm	80/70	80	150	2 ns	.05 mW	$\frac{1-3}{1000}$ C-1200 $\frac{4-10}{850}$ C-1050	Bandwidth 150 MHz *Available W/pigtail

LED VENDOR SURVEY (continued)

Manufacturer Part Number	λ peak (nm)	Temperature Tolerance Storage/ Operating (°C)	Spectral Width (nm)	Threshold Current (mA)	Rise Fall Time (ns)	Output Power (C-coupled)	Cost	Other
Fujitsu:								
FED081X	865 ±20	-50 to +90/ -40 to +90	60	150		2.5 mW	$74	Cutoff freq - 40 MHz A/GaAs
FED130JA	1300 ±40	-50 to +90/ -40 to 90	125	150		10 μW -C	$950	Cutoff freq - 8 MHz InGaAsP
FED131X	1300 ±25	-50 to 90/ -40 to 90	120	150		.6 mW	$800	Cutoff freq - 30 MHz InGaAsP
GE:								
F5D1/FSD2 F5E1/FSE2	880	-65 to 150/ -65 to 150	80	100	1.5 μs/ 1.5 μs	12 mW - E1/D1 9 mW - D2/E2		$\frac{\Delta\lambda p}{\Delta T(^\circ C)} = .3$ nm
ITT:								
T-7600 Series	1220		100	200		1.5 μW-C		Bandwidth 50 MHz

DETECTOR VENDOR SURVEY

DETECTOR VENDOR SURVEY

Manufacturer Part Number	Spectral Range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP x 10^{14}	Active Area	Capacitance pf	$f_{Cut-off}$	Cost	Other
AEG-Telefunken:											
BPW 28	400-1100		20		200 ps			1			Si avalanche
S171P	400-1100		20		200 ps			0.85			Si avalanche
S177P	400-1100		20		200 ps			0.85			Si avalanche
EG&G:											
UV-040BG	250-1150			0.65 (900)		1.0	0.81 mm^2	25		$17	$\frac{\Delta R}{\Delta T} = \frac{0.05\%}{°C}$; Si
UV-100BG	250-1150			0.65 (900)		2.5	5.1 mm^2	150		$35	$\frac{\Delta R}{\Delta T} = \frac{0.05\%}{°C}$; Si
SGD-040	350-1150	-65 to 125		0.5 (900)	3 ns	8.0	0.8 mm^2	1.2		$15	Bandwidth - 26 MHz; Si
SGD-100	350-1150	-65 to 125		0.5 (900)	5 ns	7.0	5.1 mm^2	4		$40	Bandwidth - 45 MHz; Si
SGD-160	350-1150	-65 to 125		0.5 (900)	7 ns	1.5	13.0 mm^2	9		$65	Bandwidth - 45 MHz; Si
FND-100	350-1100	-55 to 125/ -55 to 70		0.62 (900)	<1 ns	29.0	5.1 mm^2	8.5		$40	Bandwidth - 350 MHz; Si
FOD-100	350-1100	-55 to 125/ -55 to 70		0.62 (900)	<1 ns	20.0	5.1 mm^2	8.5		$45	Bandwidth - 350 MHz; Si
DT-25	350-1150	-55 to 125		0.5 (900)	5 ns	20.0	5.1 mm^2	4		$23	Bandwidth - 45 MHz; Si

W/Hz $^{1/2}$

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP x 10^{14}	Active Area	Capaci-tance pf	$f_{Cut-off}$	Cost	Other
Lasertron:											
Q-DF-T	1000-1650			0.5 (1300)				0.5			GaInAs
QD-100P	Peak 1600			0.5 (1300)	40 ps			0.5			GaInAs
QDUHS	1600			0.5 (1300)				0.5			GaInAs
Math Associates:											
E 7460		-55 to 55		0.7	20/ 150 ns	700		35			Ge
E 7462		-55 to 55		0.55	10/ 30 ns	5000		65			Ge
E 7464		-55 to 55		0.55	90/ 150 ns	70000		400			Ge
E 7466		-55 to 55		0.4	2000/ 3000 ns	-		5			Ge
E 7468		-55 to 55		0.5	1/1 ns	5000		5			Ge
Mitsubishi:	Peak										
PD-1002	~800	-55 to 150/ -40 to 110	77			1	$3x10^{-2}$	1.5	2 GHz		Si APD
PD-1302	~800	-55 to 150/ -40 to 110	77			1	$3x10^{-2}$	1.5	2 GHz		Si APD

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP x 10^{14}	Active Area	Capacitance pF	$f_{Cut-off}$	Cost	Other
PD-1005	~800	-55 to 150/ -40 to 110	77			1	$2x10^{-1}$	7	0.4 GHz		Si APD
PD-1305	~800	-55 to 150/ -40 to 110	77			1	$2x10^{-1}$	7	0.4 GHz		Si APD
PD-7001	1-1.6 μm	-30 to 100/ -30 to 80	50 (1.6 μ)				$8x10^{-3}$	<5	$6x10^{8}$ Hz		Si APD
Silicon Detector Corp.:											
SD056-12-12-001				0.45	25 ns	1.2	1.32	150			Si
Optron:											
OP905	300-1100	-40 to 80		0.49	200 ns	4	7.5 mm^2	110			Si pin
OP915	250-1200	-40 to 80		0.6	50 ns	7	7.5 mm^2	25			Si pin
OP905F	750-1100	-40 to 80		0.37	200 ns	5	7.5 mm^2	110			Si pin
OP915F	750-1100	-40 to 80		0.58	50 ns	7	7.5 mm^2	25			Si pin
OP903		-65 to 150/ -55 to 125			200 ns			200			Si pin
OP913		-65 to 150/ -55 to 125			50 ns			70			Si pin - collimating lens
OP903W		-65 to 150/ -55 to 125			200 ns			200			Si pin - flat lens

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP x 10^{14}	Active Area	Capacitance pf	$f_{Cut-off}$	Cost	Other
OP913W		-65 to 150/ -55 to 125			50 ns			70			Si pin - flat lens
OP790		-65 to 150/ -55 to 125			600 ns						
Plessey:	Peak										
HRD200	1300	-65 to 125/ -40 to 90		0.5	1 ns	15	0.01 μm^2	2			GaInAs - available with pigtail
RCA:											
C 30817	400-1100		83	0.6	2 ns	1.5	0.5 mm^2	2			Si avalanche
C 30872	400-1100		83	0.6	2 ns	3	7 mm^2	10			Si avalanche
C 30884	400-1100		83	0.6	1 ns	1.3	0.5 mm^2	4			Si avalanche
C 30895	400-1100		83	0.6	2 ns	1.5	0.5 mm^2	2			Si avalanche
C 30902E	400-1100		83	0.6	0.5 ns	3	0.2 mm^2	1.6			Si avalanche
C 30812	400-1400	-40 to 80	83 (900) 60 (1060)	0.6 (900) 0.5 (1060)	12 ns (1060)	15	0.5 mm^2	3			Si pin
C 30900E	400-1100	-40 to 80	83 (900)	0.6	6 ns (900)	50	5 mm^2	5			Si pin
C 30807	400-1100	-40 to 80	83 (900) 17 (1060)	0.6 (900) 0.15 (1060)	3 ns (900) 5 ns (1060)	10	0.8 mm^2	2.5			Si pin

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP x 10^{14}	Active Area	Capacitance pf	$f_{Cut\text{-}off}$	Cost	Other
C 30808	400-1100	-40 to 80	83 (900) 17 (1060)	0.6 (900) 0.15 (1060)	5 ns (900) 8 ns (1060)	15	5 mm^2	6			Si pin
C 30831	400-1100	-40 to 80	83 (900) 17 (1060)	0.6 (900) 0.15 (1060)	3 ns (900) 5 ns (1060)	10	0.2 mm^2	2			Si pin
C 30916E	400-1100	-40 to 70	83 (900) 18 (1060)	50 (900) 12 (1060)	4 ns	1.5 (900) 6 (1060)	1.77 mm^2	5			Si avalanche
Ford:		Max Limits									
L4501	500-1000	100/85	50				0.006 mm^2	0.8	25 GHz		Si
L4502	500-1000	100/85	50				0.01 mm^2	2.5	15 GHz		Si
L4520	500-1000	100/85	30				0.03 mm^2	5	1.5 GHz		Ge
L4503	300-1500	100/85		0.6			3.5 mm^2	5.5	300 MHz		D* = 7 x 10^{12}; Si
L4504	300-1500	100/85		0.6			3.5 mm^2	4	600 MHz		D* = 7 x 10^{12}; Si
L4506	300-1500	100/85		0.6			3.5 mm^2	10	600 MHz		D* = 7 x 10^{12}; Si
L4509	400-1500	100/85		0.6			3.5 mm^2	15	1200 MHz		D* = 7 x 10^{12}; Si

*fw/ $\sqrt{Hz}$

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP* x 10^{14}	Active Area	Capacitance pf	$f_{Cut-off}$	Cost	Other
L4521	1000-1800	100/85	80	0.97			0.81 mm^2	40	500 MHz		Ge
L4412	350-1200	-64 to 130 -65 to 125			0.075 μs 2.5 μs						Si pin
Motorola:											
MFPD104F	250-1200	-30 to 100/ -30 to 85		0.4	6 ns	50		3.2			Si pin
MFOD102F	250-1200	-30 to 100/ -30 to 85		0.4	20 ns	50		3.2			Si pin
MFOD100F	250-1200	-30 to 100/ -30 to 85		0.5	1.5 ns			4			Si pin
MFOD200	425-1125	-30 to 100/ -30 to 85		18							NPN Si phototransistor
UDT:	Peak										
FO-02-E	900	-55 to 100/ -30 to 85		0.5	2 ns	5	0.2 mm^2	2		$8.95	Si pin
FO-04-E	900	-55 to 100/ -30 to 85		0.5	4 ns	10	0.8 mm^2	4		$9.95	Si pin
FO-30-E	900	-55 to 100/ -30 to 85		0.5	30 ns	20	3.2 mm^2	10		$11.95	Si pin
FO-02-200	900	-55 to 100/ -30 to 85		0.5	2 ns	5	0.2 mm^2	2		-	Si pin

$^{*}\frac{fw}{\sqrt{Hz}}$

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP x 10^{14}	Active Area	Capacitance pf	$f_{Cut-off}$	Cost	Other
FO-02-400	900	-55 to 100/ -30 to 85		0.5	2 ns	5	0.2 mm^2	2		$18.95	Si pin
PIN 020A	900	-55 to 100/ -30 to 85		0.52	5 ns	1	0.2 mm^2	4		$1450	Si pin
PIN 025A	900	-55 to 100/ -30 to 85		0.52	5 ns	1	0.2 mm^2	4		-	Si pin
PIN 020B	900	-55 to 100/ -30 to 85		0.52	5 ns	5	0.2 mm^2	4		$13.00	Si pin
PIN 025B	900	-55 to 100/ -30 to 85		0.52	5 ns	5	0.2 mm^2	4		-	Si pin
PIN 040A	900	-55 to 100/ -30 to 85		0.52	5 ns	2	0.8 mm^2	16		-	Si pin
PIN 045A	900	-55 to 100/ -30 to 85		0.52	5 ns	2	0.8 mm^2	16		$14.75	Si pin
PIN 040B	900	-55 to 100/ -30 to 85		0.52	5 ns	10	0.8 mm^2	16		$13.25	Si pin
PIN 045B	900	-55 to 100/ -30 to 85		0.52	5 ns	10	0.8 mm^2	16		-	Si pin

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time (ns)	NEP x 10^{14}	Active Area	Capacitance pF	$f_{Cut-off}$	Cost	Other
NEC											
NDL 2102	500-950	-65 to 150	70		1			1.5			Si pin
NDL 2104	500-1025	-65 to 150	70		4			2.8			Si pin
NDL 2208	500-1150	-65 to 150 coupled: -30 to 80	85		10			1.5			Si pin
NDL 1202	500-1100	-65 to 150 coupled: -20 to 60	70		1			1.3			Si Avalanche
NDL	500-1100	-60 to 150	65 (630)	.33 (620) .43 (830)	.5 (630) 1 (830)			2.5			
VACTEC	PEAK										
VTP8551	940	-40 to 80			50			25			Si pin
VTP8552	940	-40 to 80			50			25			Si pin
VTP8651	940	-40 to 80			50			25			Si pin
VTP8652	940	-40 to 80			50			25			Si pin

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP x 10^{14}	Active Diameter	Capacitance pf	$f_{Cut-off}$ (MHz)	Cost	Other
Fujitsu											
FPD150C	500-1600	-65 to 90/ -40 to 70	73				100 μm	2	600		
FID080MA	peak-830	-65 to 150/ -40 to 80	78				400 μm	2	300		Si pin
FID080ML	peak-830	-65 to 150/ -40 to 80	68				400 μm	2	300		Si pin
FID081W	peak-830	-65 to 150/ -40 to 80	72				1 mm	7	200		Si pin
FPD080MA	peak-830	-65 to 150/ -40 to 80	78				300 μm	1.5	300		Si Avalanche
FPD080CA	peak-830	-65 to 150/ -40 to 80	78				300 μm	1.5	300		Si Avalanche
FPD081MA	peak-830	-65 to 150/ -40 to 80	60				300 μm	1.5	300		Si Fibered
FPD140M3	peak-1300	-65 to 90/ -40 to 70	70				300 μm	1.5	600		Ge Avalanche
FPD140C	peak-1300	-65 to 90/ -40 to 70	70				100 μm	2	200		Ge Avalanche
FPD150M	peak-1300	-65 to 90/ -40 to 70	73				100 μm	8	200		Ge Avalanche
FID151W	peak-1300	-55 to 150/ -40 to 100	75				1 mm	10	200		Ge Avalanche

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Spectral range	Storage/ Operating (°C)	QE (%)	A/W (λ)	Rise/ Fall Time	NEP x 10^{14}	Active Diameter	Capacitance pf	$f_{Cut-off}$ (MHz)	Cost	Other
Laser Diode Labs											
CG 4000	1000-1600	-10 to 75/ -10 to 75			1 ns		100 μm	3			Ge Avalanche
CG 4100	1000-1600	-10 to 75/ -10 to 75			1 ns		70 μm	1.4			Ge Avalanche
CG 4200	1000-1600	-10 to 75/ -10 to 75/			1.5 ns		200 μm	9			Ge Avalanche
DIR-170	350-1150	-40 to 70/ 0 to 70		.2 (670) .3 (900)	3 ns	20					Si, fibered pin
Judson	peak										
J16-18A	1500			.75		300		4	300	$115	Ge $D^{*\dagger}$ = .8 x 10^{-11}
J16-18B	1500			.75		300		4	300	$145	Ge $D^{*\dagger}$ .8 x 10^{-11}

173/174

† $\frac{cm\,Hz^{1/2}}{W}$

WDM COUPLERS

WDM COUPLER VENDOR SURVEY (continued)

Manufacturer Part Number	Wavelength Ranges (nm)	Type of Technology	Channels	Loss (dB) Insertion	Crosstalk (dB)	Cost	Other
Kaptron							
FOWD-1-2	400-2500	Coating	Multi	1	-	$1000	Demux
FOWD	400-2500	Dichroic	2	1	-	$1000	Demux
FOWM-1-2	400-2500	Coating	Multi	0.5	-	$825	Mux
FOWM	400-2500	Dichroic	2	0.5	-	$825	Mux
FOD-3	400-2500	Coating	Multi	Throughput	-	$825	Bidirectional
FOBC-A	400-2500	Dichroic	2	4 dB	-		
FOD-4	400-2500	Coating	Multi	(1 dB)	-		
FOBC	400-2500	Dichroic	2		-		
ITT							
T-7280	1-800-860	Dichroic	2	1→3 1.25	1→2 65		
	2-1000-1100	Dichroic		3→2 1.25	3 (with λ,)→2 35 dB		
T-7281	1-1000-1100	Dichroic	2	1→3 1.25	1→2 65		
	2-1000-1100	Dichroic	2	3→2 1.25	3 (with λ,)→2 35 dB		

DETECTOR VENDOR SURVEY (continued)

Manufacturer Part Number	Wavelength Ranges (nm)	Type of Technology	Channels	Loss (dB) Insertion	Crosstalk (dB)	Cost	Other
ITT (continued)							
T-7292	1-800-900	Dichroic	2	$1 \rightarrow 3$ 1.25	$1 \rightarrow 2$ 65		
	2-1200-1400	Dichroic		$3 \rightarrow 2$ 1.25	3 (with λ_1)$\rightarrow 2$ 35 dB		
T-7293	1-1200-1400	Dichroic	2	$1 \rightarrow 3$ 1.25	$1 \rightarrow 2$ 65		
	2-800-900	Dichroic	2	$3 \rightarrow 2$ 1.25	3 (with λ_1)$\rightarrow 2$ 35 dB		
				(channel loss)*			
NEC							
OD-8672	1-800 2-860 3-890	Dispersive	3	Bidirect 8 Unidirect 6			SXR-Bidirect 17 dB -Unidirect 25 dB
OD-8671 (LED)	1-830 2-890	Dichroic	2	Bidirect 9 Unidirect 9			SXR-30 dB
OD-8671 (LD)	1-780 2-880	Dichroic	2	Bidirect 8 Unidirect 6			SXR-19 dB

---

* Pair of multiplexer/demultiplexer.

APPENDIX C

OPTICAL CIRCUIT ANALYSIS PROGRAM

TABLE OF CONTENTS

C-1.0 DATA BASE STRUCTURE

The Optical Circuit Analysis Program (OCAP) data base structure provides for the maintenance of a bank of information on fiber optic ›mponents and allows this information to be accessed as required during system analysis calculations. Operations possible with the data base are (1) addition of a component, (2) inquiry about a component, (3) update of component information, (4) deletion of a component, and (5) listing of component data. These operations are designed for optimum efficiency for an operator using a video computer terminal and safeguards are provided to minimize accidental loss of data base contents.

A nine-digit reference number (also referred to as a key number) is used to identify each component in the data base. The first digit of the reference number specifies the general component type, the next four numbers specifically identify the component, and the last four numbers specify the optical path (if more than one) through the component that the data entries apply to. Component types and their respective codes are

Component	Type Number
Source	0
Filter	1
Fiber	2
Coupler	3
Detector	4

The four digits used to specifically identify the component are, in general, arbitrarily assigned as components are added to the data base. An example reference number, such as 300060502, would be for an optical coupler, unit type 0006, port 5 input, and port 2 output. The OCAP Data Base List (Section 2.0) contains all of the components used on the AFWAL study program.

C-2.0 DATA BASE COMPONENTS LIST

The Data Base Components List is shown in Table C-2.0-1.

Table C-2.0-1. Data Base List for Optical Circuit Analysis Program.

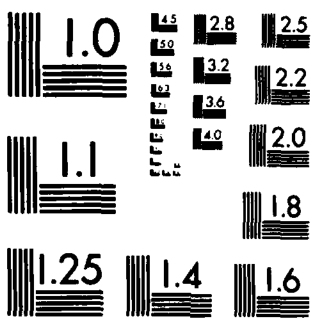
Component	Reference No	Description		System
Sources	000010000	800 nm AlGaAs		I, III
	000020000	900 nm GaAs		I, III
	000030000	1550 nm InGaAsP		III
	000040000	1300 nm InGaAsP		III
	000050000	760 nm AlGaAs		II
	000060000	772.5 nm AlGaAs		II
	000070000	785 nm AlGaAs		II
	000080000	797.5 nm AlGaAs		II
	000090000	810 nm AlGaAs		II
	000100000	822.5 nm AlGaAs		II
	000110000	835 nm AlGaAs		II
	000120000	847.5 nm AlGaAs		II
Filters	100010000	LWP		III
	100020000	LWP		I
	100030000	SWP reflection	used in dichroic couplers	I, III
	100040000	SWP transmission		I, III
	100060000	LWP		I
	199990000	Dummy - no loss		

AD-A125 749 A STUDY OF WAVELENGTH DIVISION MULTIPLEXING FOR AVIONICS APPLICATIONS..(U) ITT ELECTRO-OPTICAL PRODUCTS DIV ROANOKE VA J C WILLIAMS ET AL. AUG 82 ITT-82-32-02 3/3

UNCLASSIFIED AFWAL-TR-82-1118 F33615-81-C-1481 F/G 9/3 NL

END
DATE
FILMED
4 83
DTIC

M-2



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Table C-2.0-1. Data Base List for Optical Circuit Analysis Program (continued).

Component	Reference No	Description	System
Fiber	200010000		I, II, III
	299990000	Dummy - no loss	
Detectors	400010000	Si, peak 1050 nm	I, II, III
	400020000	InGaAs	I
Couplers	300010000	Dichroic coupler	III
	300020000	Dichroic coupler	III
	300030000	Diffraction grating coupler	II
	300040000	Dichroic coupler	I
	300050000	Dichroic coupler	I
	300060000	Diffraction grating coupler	II

C-3.0 DATA BASE COMPONENT EXAMPLES FOR OPTICAL CIRCUIT ANALYSIS PROGRAM

This section contains graphical examples of OCAP data base information. These examples cover sources, filters, detectors, and couplers, the components identified to be most wavelength sensitive. The examples are shown in Table C-3.0-1.

Table C-3.0-1. Data Base Component Examples for Optical Circuit Analysis Program.

Component Type	Reference Number	Description	Figure
Source	000010000	800 nm LED	C-3.0-1
Source	000050000	760 nm ILD	C-3.0-2
Source	000030000	1550 nm ILD	C-3.0-3
Filter	100010000	Long wavelength pass	C-3.0-4
Detector	400010000	Si photodiode	C-3.0-5
Coupler	300010103	Bidirectional coupler	C-3.0-6
Coupler	300010302	Bidirectional coupler	C-3.0-7

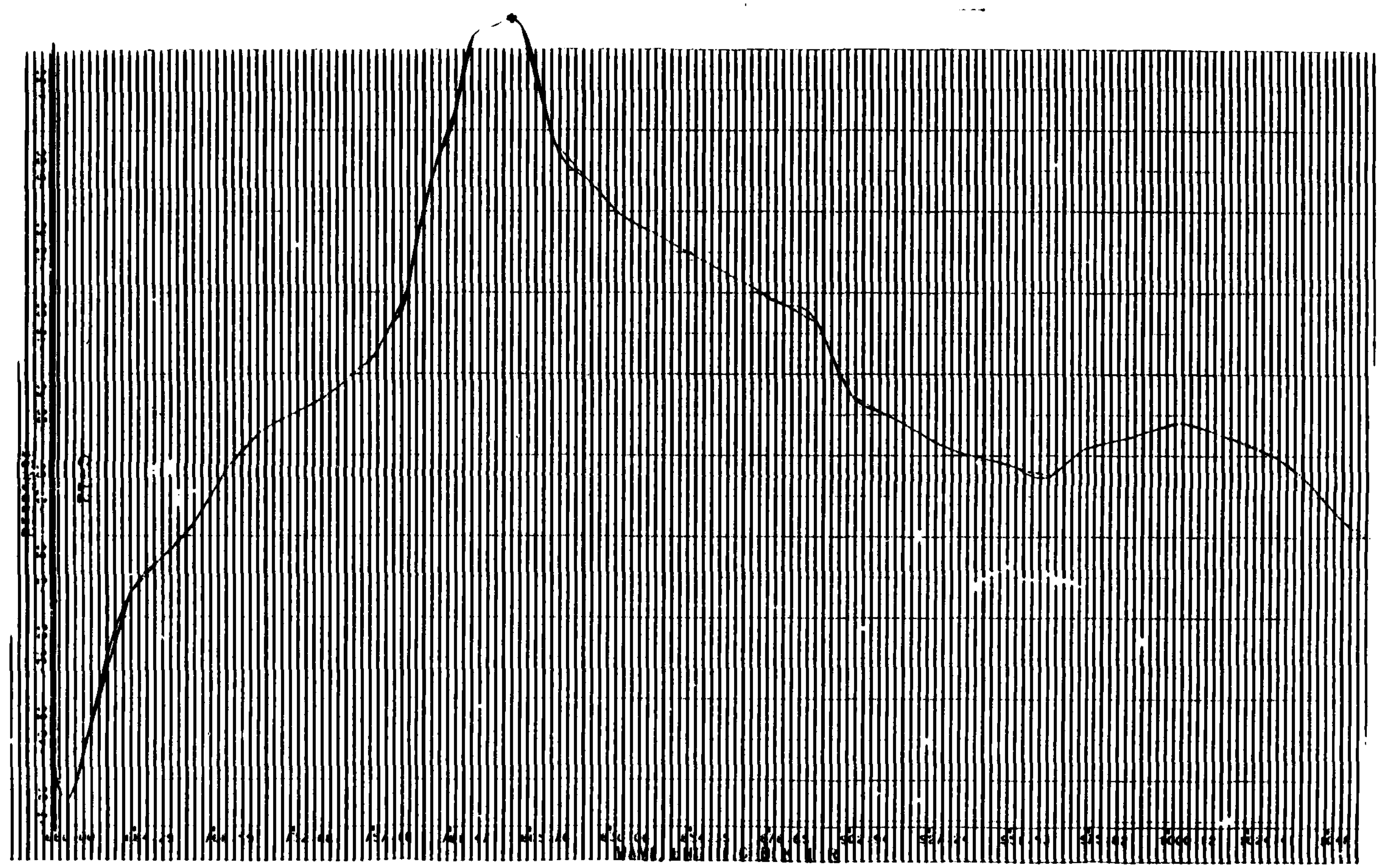


Figure C-3.0-1. Relative Response (dB) of Source 000010000 (800 nm LED) Versus Wavelength (nm).

23202

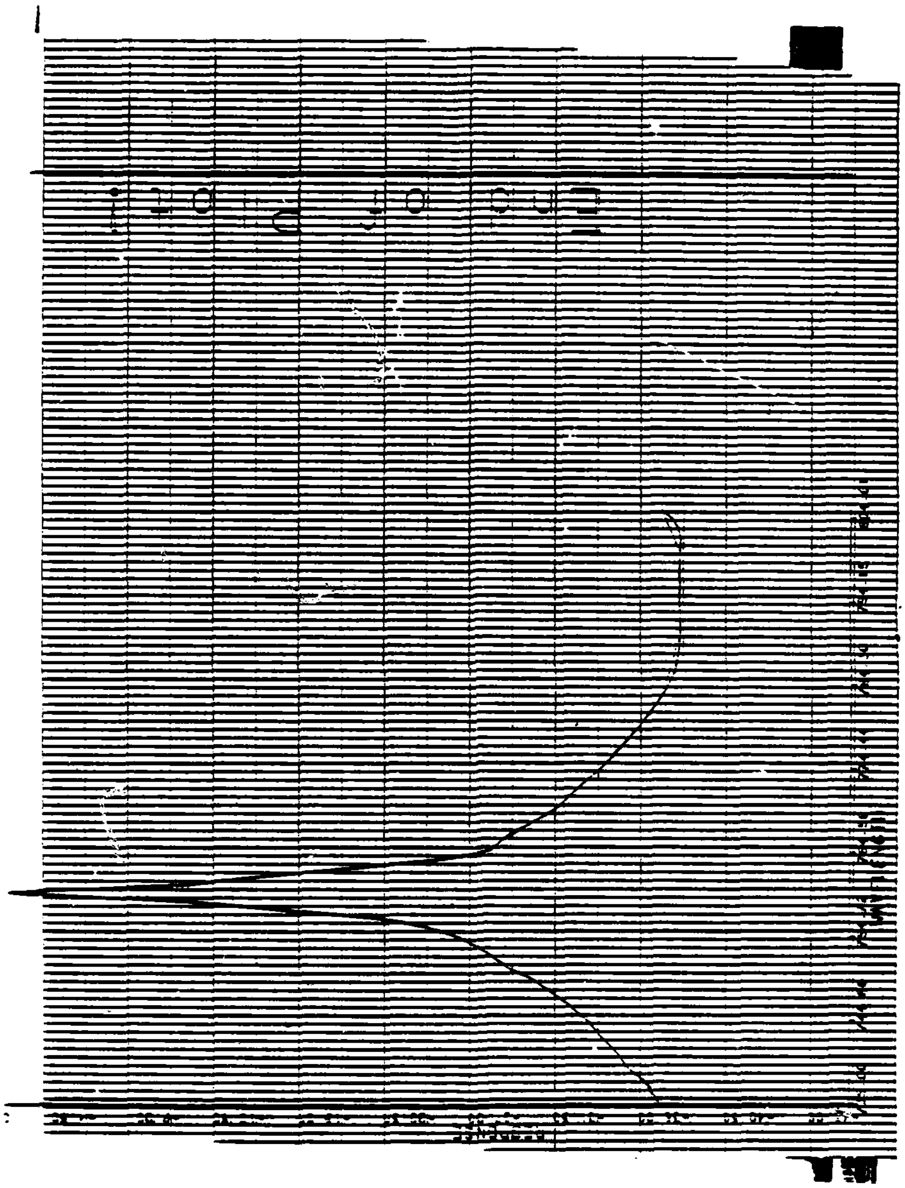


Figure C-3.0-2. Relative Response (dB) of Source 000050000 (760 nm ILD) Versus Wavelength (nm).

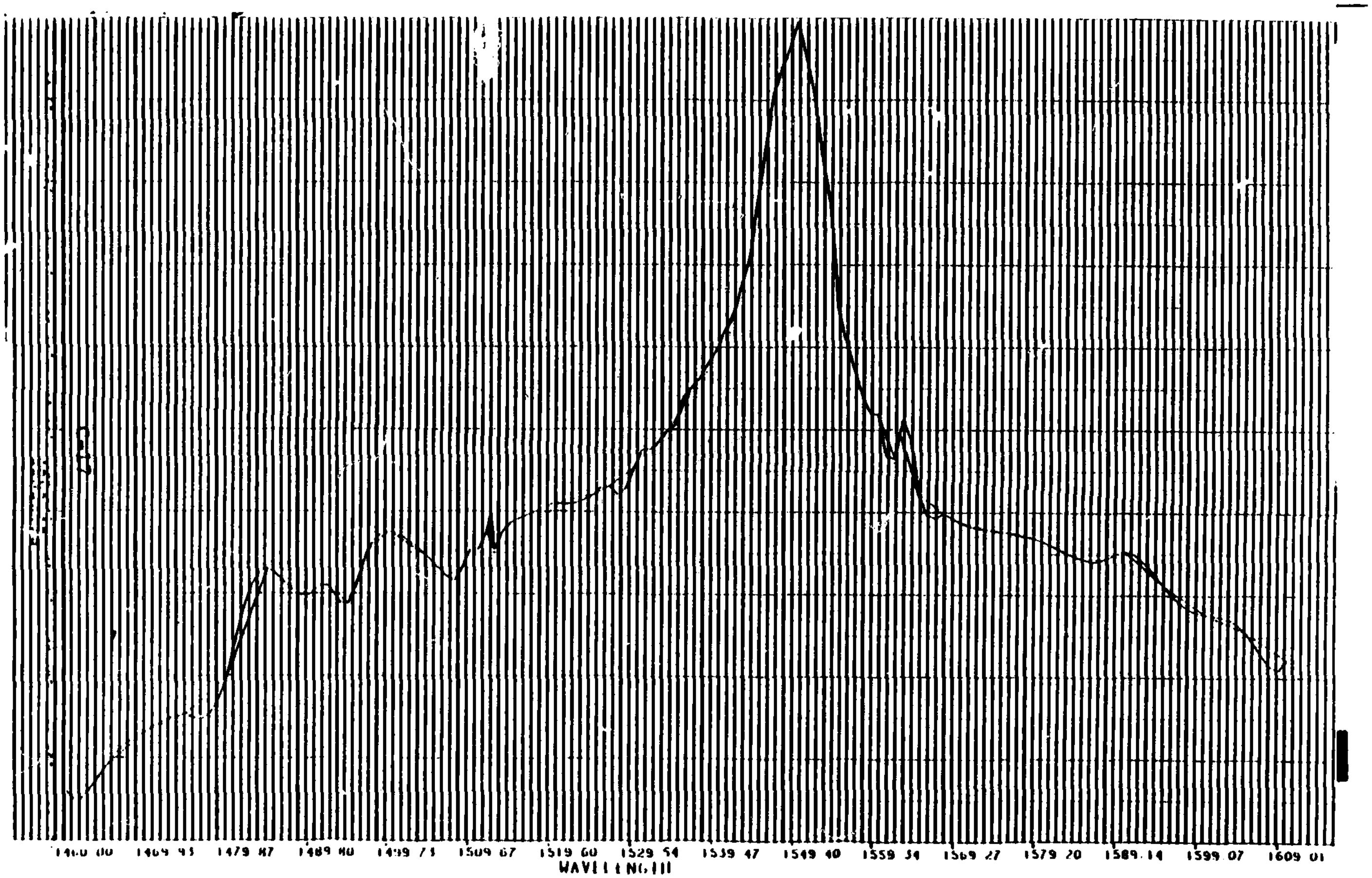


Figure C-3.0-3. Relative Response (dB) of Source 000030000 (1550 nm LED) Versus Wavelength (nm).

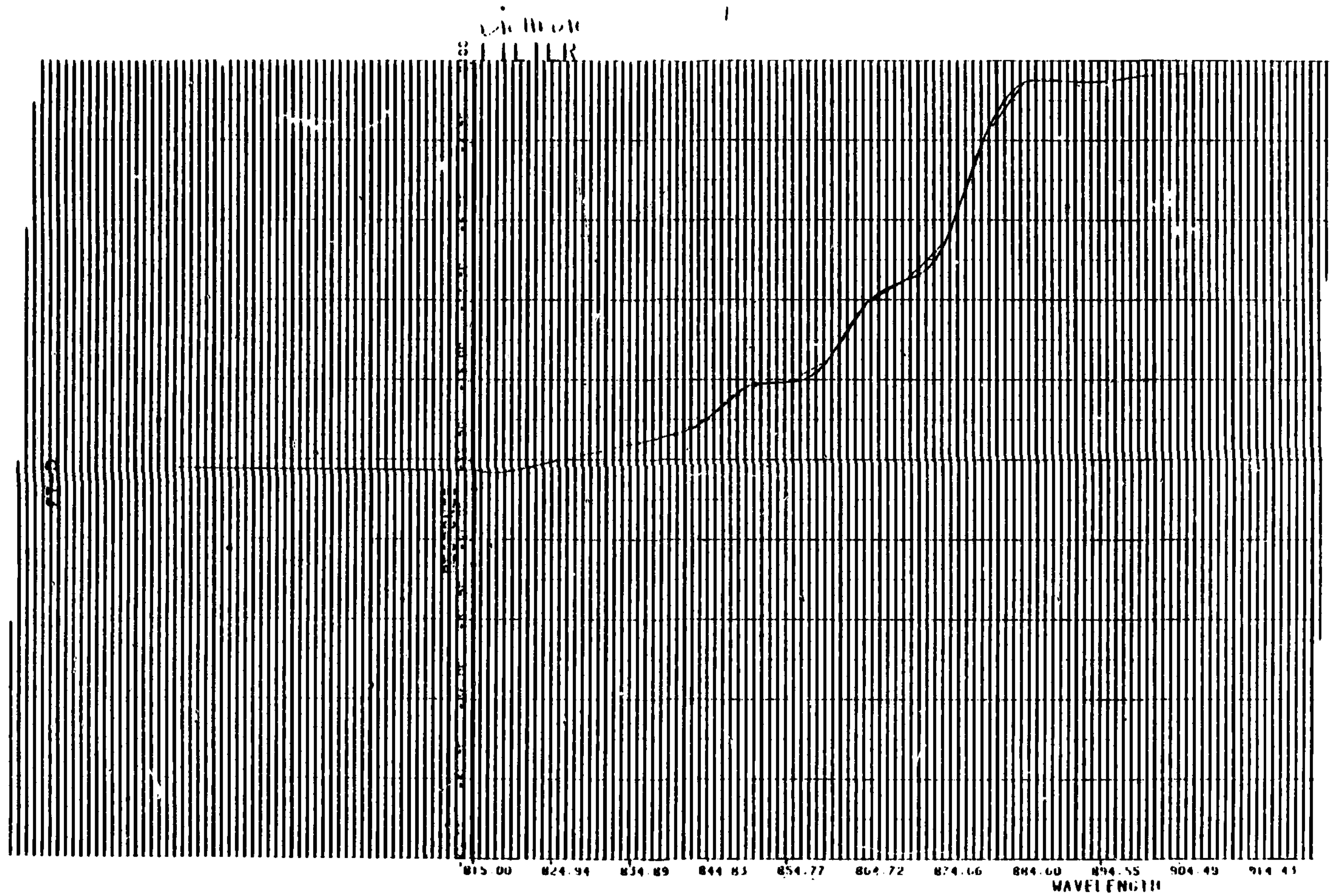


Figure C-3.0-4. Transmission Response (dB) of Filter (100010000) Versus Wavelength (nm).

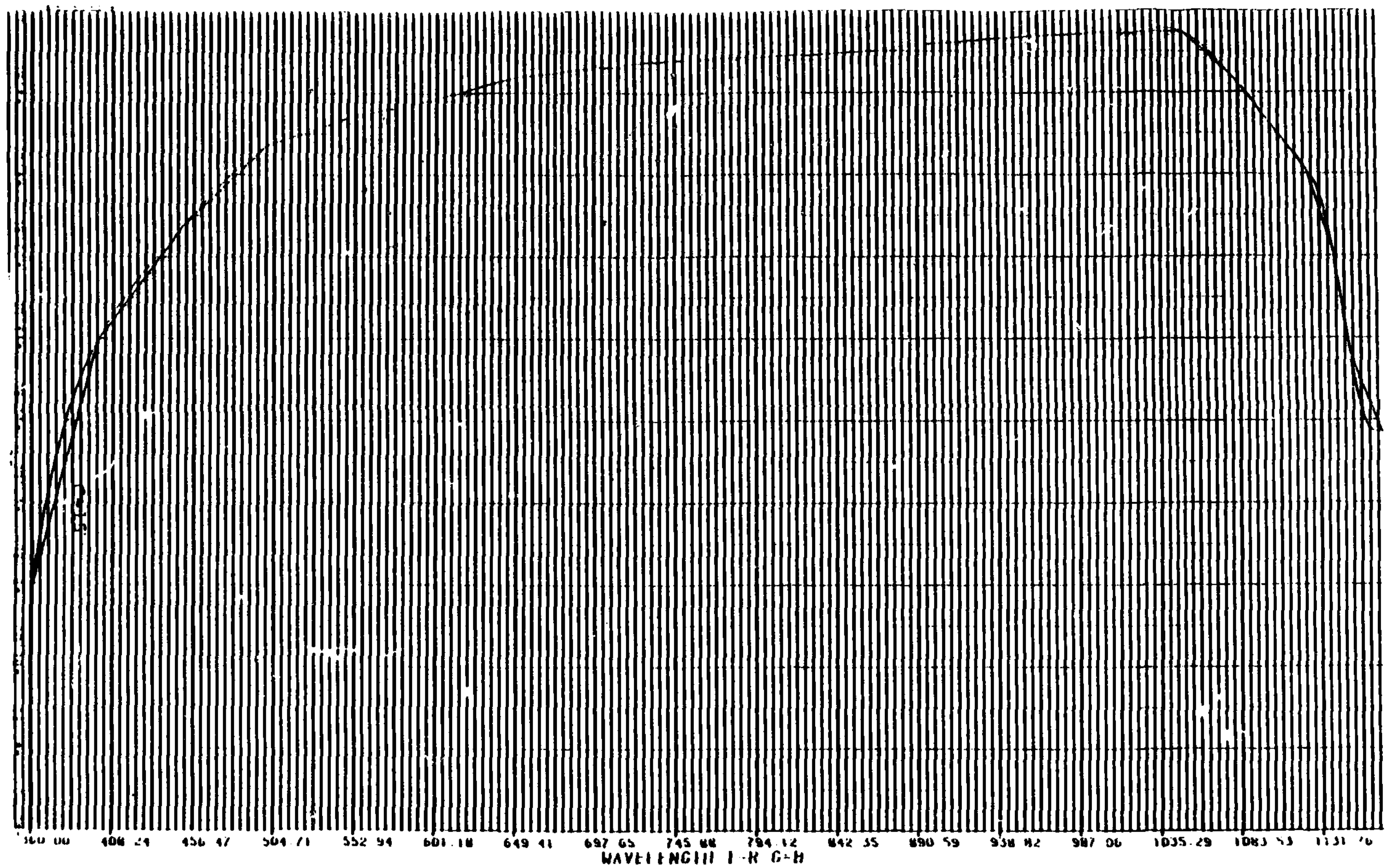


Figure C-3.0-5. Relative Response (dB) of Silicon Photodiode (400010000) Versus Wavelength (nm).

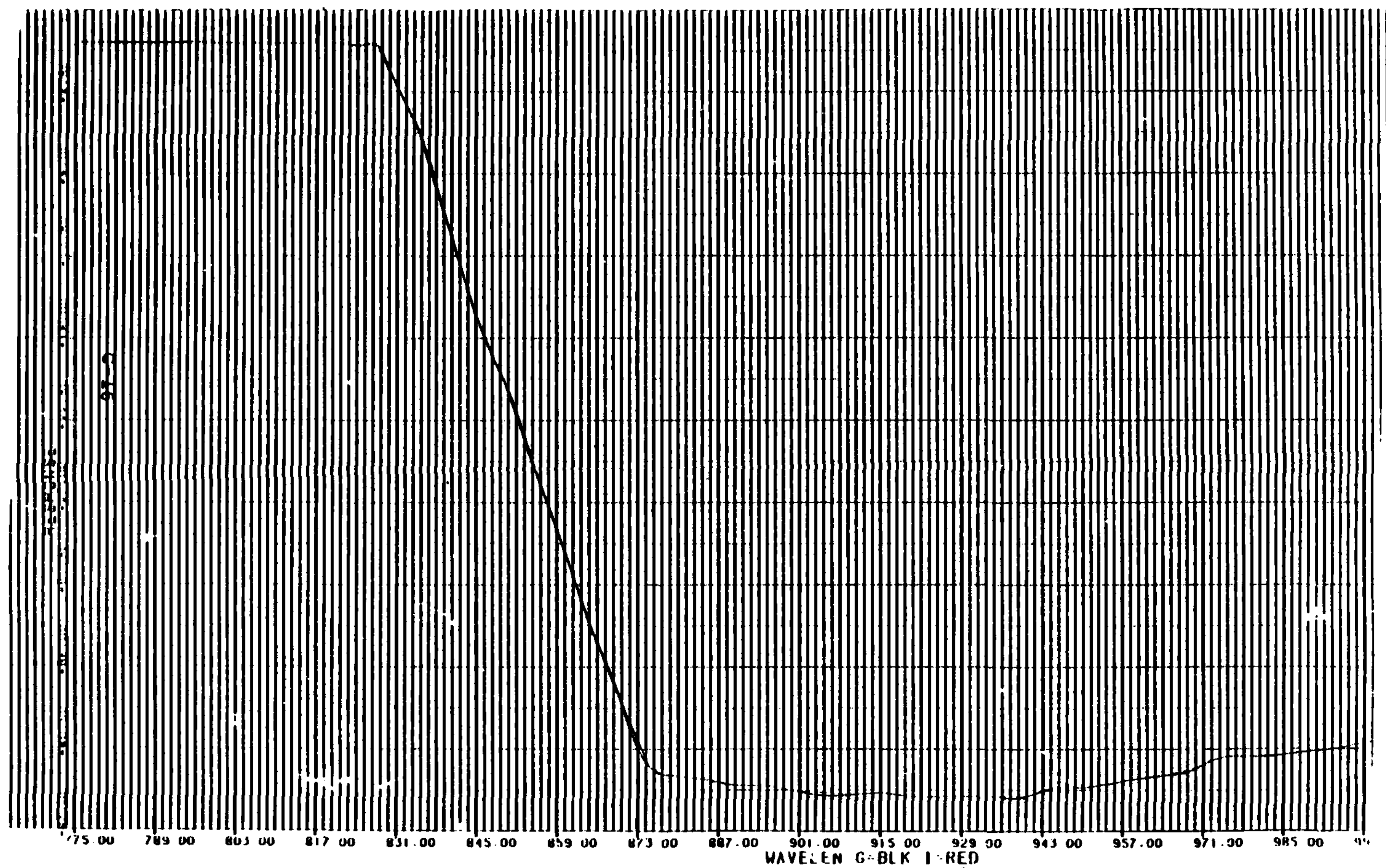


Figure C-3.0-6. Transmission Response (dB) of Coupler 300010103 Versus Wavelength (nm).

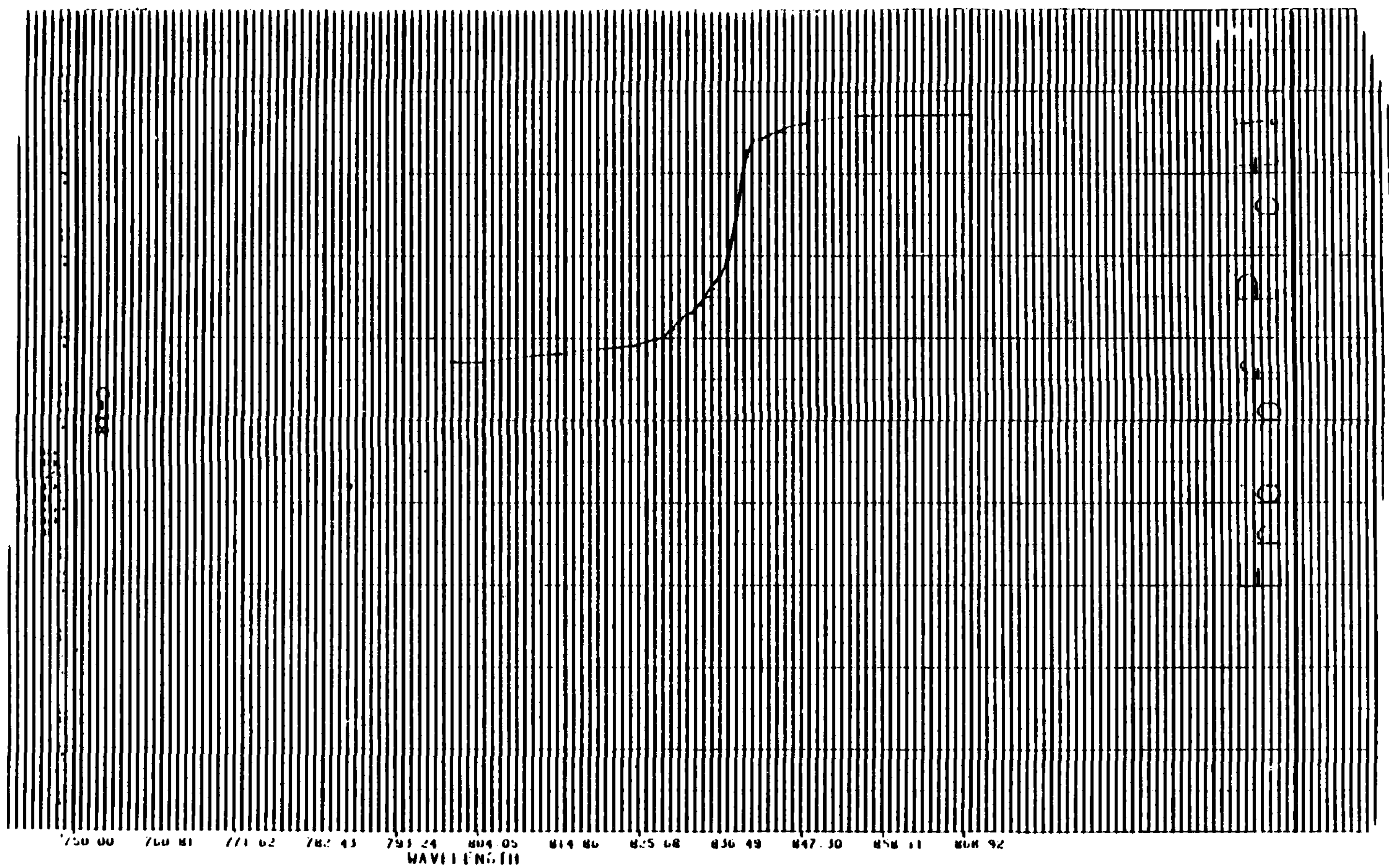


Figure C-3.0-7. Transmission Response (dB) of Coupler 300010302 Versus Wavelength (dB).

C-4.0 SYSTEM ANALYSIS CODE EXAMPLE FOR OPTICAL CIRCUIT ANALYSIS PROGRAM

The attached computer program listing is the main program FORTRAN code for the analysis of Air Force System III. This program is a good example of the programs for all the wavelength division multiplexing systems and illustrates the flow of the program and the size of the code required.

The program begins with initialization statements afte[illegible] hich the system specifications are read from a file previously [illegible] up. This system specification file defines the wavelength [illegible], the number of points for the numerical analysis, and the particular components used. Error checking is provided by printing out a complete copy of the specification file as it is read. The program user can compare this printout with the desired system configuration and can make corrections if necessary. Calculation of the power which flows through each optical path of the system is done next in the nested loops which end at statement 200. This calculation is equivalent to sequentially "turning on" the sources in the WDM system and measuring the power at each detector. After all optical paths called out have been analyzed, a system matrix printout is made and total crosstalk is determined.

C-5.0 EXAMPLE PROGRAM RUN PRINTOUTS

Example program run printouts are shown in Figure C-5.0-1.

```
C       THIS PROGRAM ANALYZES AIR-FORCE SYSTEM-3.
C       PROGRAM AUTHOR: B.VIDULA ....SEPT.81-JAN.82...
        CHARACTER*9 SKEYNO(2),C1KEYNO,F1KEYNO,CNKEYNO,SCKEYNO
        CHARACTER*9 F2KEYNO,C2KEYNO,DKEYNO(2)
        CHARACTER*9 FL1KEYNO(2),FL2KEYNO(2)
        INTEGER*4 C1KEY,C2KEY,CKKKKT1,CKKKKT2
        INTEGER NWPT,FP1,SP,DP,FP2
        INTEGER NMAX,NCAT,ISTCAT,NTAB,ISTTAB,XC
        REAL PTCTKT,PTCTK,PLOSS
        REAL FL1DLAMDA,FL1DLOSS,FL2DLAMDA,FL2DLOSS
        REAL STLAMDA,SPLAMDA,C1DLOSS,C1DLAMDA,CNLOSS,LENGTH1
        REAL F1DLOSS,F1DLAMDA,SCLOSS,LENGTH2,F2DLOSS,F2DLAMDA
        REAL C2DLOSS,C2DLAMDA,SCOUPWR,SDLAMDA,DDLOSS
        REAL CDLAMDA,PWR
        REAL SPSIZE,RVALUE,IVALUE,LAMDA,YC,XT,YT
        DIMENSION PLOSS(2,2),PTCTK(2)
        DIMENSION DDLAMDA(2),PWR(2,2)
        DIMENSION FL1DLAMDA(2),FL1DLOSS(2),FL2DLOSS(2),FL2DLAMDA(2)
        DIMENSION SCOUPWR(2),SDLAMDA(2),DDLOSS(2),SP(2),DP(2)
        COMMON/COMINI/ NMAX,RVALUE(1501),IVALUE(1501),LAMDA(1501)
        COMMON/COMCAT/ NCAT,ISTCAT,XC(144),YC(144)
        COMMON/COMTAB/ NTAB,ISTTAB,XT(100),YT(100)
        COMMON/COMMIS/ SPSIZE
C       READ THE SYSTEM SPECS
        READ(2,*) STLAMDA,SPLAMDA,NWPT
        WRITE(3,*) STLAMDA,SPLAMDA,NWPT
        DO 15 I=1,2
        READ(2,*) SKEYNO(I),SCOUPWR(I),SDLAMDA(I)
        WRITE(3,*) SKEYNO(I),SCOUPWR(I),SDLAMDA(I)
 15     CONTINUE
        DO 11 I=1,2
        READ(2,*) FL1KEYNO(I),FL1DLOSS(I),FL1DLAMDA(I)
        WRITE(3,*) FL1KEYNO(I),FL1DLOSS(I),FL1DLAMDA(I)
 11     CONTINUE
        READ(2,*) C1KEY,C1DLOSS,C1DLAMDA
        WRITE(3,*) C1KEY,C1DLOSS,C1DLAMDA
        READ(2,*) SP(1),SP(2),FP1
        WRITE(3,*) SP(1),SP(2),FP1
        READ(2,*) CNKEYNO,CNLOSS
        WRITE(3,*) CNKEYNO,CNLOSS
        READ(2,*) F1KEYNO,LENGTH1,F1DLOSS,F1DLAMDA
        WRITE(3,*) F1KEYNO,LENGTH1,F1DLOSS,F1DLAMDA
        READ(2,*) CNKEYNO,CNLOSS
        WRITE(3,*) CNKEYNO,CNLOSS
        READ(2,*) SCKEYNO,SCLOSS
        WRITE(3,*) SCKEYNO,SCLOSS
        READ(2,*) CNKEYNO,CNLOSS
        WRITE(3,*) CNKEYNO,CNLOSS
        READ(2,*) F2KEYNO,LENGTH2,F2DLOSS,F2DLAMDA
        WRITE(3,*) F2KEYNO,LENGTH2,F2DLOSS,F2DLAMDA
        READ(2,*) CNKEYNO,CNLOSS
        WRITE(3,*) CNKEYNO,CNLOSS
        READ(2,*) C2KEY,C2DLOSS,C2DLAMDA
        WRITE(3,*) C2KEY,C2DLOSS,C2DLAMDA
        READ(2,*) DP(1),DP(2),FP2
        WRITE(3,*) DP(1),DP(2),FP2
        DO 12 I=1,2
        READ(2,*) FL2KEYNO(I),FL2DLOSS(I),FL2DLAMDA(I)
        WRITE(3,*) FL2KEYNO(I),FL2DLOSS(I),FL2DLAMDA(I)
 12     CONTINUE
        DO 65 J=1,2
```

Figure C-5.0-1. Example Program Run Printout (Sheet 1 of 3).

```
      READ(2,*) DKEYNO(J),DDLOSS(J),DDLAMDA(J)
      WRITE(3,*) DKEYN  J),DDLOSS(J),DDLAMDA(J)
65    CONTINUE
      WRITE(3,213)
213   FORMAT(1X,'-----------------------------------------')
C     CALL THE SUBROUTINES AND ANALYZE
      DO 200 I=1,2
      DO 200 J=1,2
      CALL INIT(STLAMDA,SPLAMDA,NWPT)
C     WRITE(3,*) SKEYNO(I)
      CALL SOURCE(SKEYNO(I),SCOUPWR(I),SDLAMDA(I))
C     WRITE(3,*) FL1KEYNO(I)
      CALL FILTER(FL1KEYNO(I),FL1DLOSS(I),FL1DLAMDA(I))
      CKKKKT1=C1KEY*10000+SP(I)*100+FP1
      ENCODE(9,100,C1KEYNO) CKKKKT1
100   FORMAT(I9)
C     WRITE(3,*) C1KEYNO
      CALL COUPLER(C1KEYNO,C1DLOSS,C1DLAMDA)
C     WRITE(3,*) CNKEYNO
      CALL CONNECTOR(CNKEYNO,CNLOSS)
C     WRITE(3,*) F1KEYNO
      CALL FIBER(F1KEYNO,LENGTH1,F1DLOSS,F1DLAMDA)
C     WRITE(3,*) CNKEYNO
      CALL CONNECTOR(CNKEYNO,CNLOSS)
C     WRITE(3,*) SCKEYNO
      CALL ISTARCPLR(SCKEYNO,SCLOSS)
C     WRITE(3,*) CNKEYNO
      CALL CONNECTOR(CNKEYNO,CNLOSS)
C     WRITE(3,*) F2KEYNO
      CALL FIBER(F2KEYNO,LENGTH2,F2DLOSS,F2DLAMDA)
C     WRITE(3,*) CNKEYNO
      CALL CONNECTOR(CNKEYNO,CNLOSS)
      CKKKKT2=C2KEY*10000+FP2*100+DF(J)
      ENCODE(9,100,C2KEYNO) CKKKKT2
C     WRITE(3,*) C2KEYNO
      CALL COUPLER(C2KEYNO,C2DLOSS,C2DLAMDA)
C     WRITE(3,*) FL2KEYNO(J)
      CALL FILTER(FL2KEYNO(J),FL2DLOSS(J),FL2DLAMDA(J))
C     WRITE(3,*) DKEYNO(J)
      CALL DETECTOR(DKEYNO(J),DDLOSS(J),DDLAMDA(J))
      CALL INTGRT(PWR(I,J))
C     WRITE(3,207)
207   FORMAT(1X,T10,'POWER AT DETECTOR ----- microWATTS')
C     WRITE(3,*) PWR(I,J)
      PLOSS(I,J)=10.0*ALOG10(PWR(I,J)/SCOUPWR(I))
C     WRITE(3,208)
208   FORMAT(1X,'-----------------------------------------')
200   CONTINUE
C     MATRIX PRINTOUT FORMAT
      WRITE(3,212)
212   FORMAT(1X,18X,'---LOSS MATRIX--dB--------',/)
      WRITE(3,213)
213   FORMAT(1X,25X,'DETECTORS',//)
      WRITE(3,214)
214   FORMAT(1X,'SOURCES',/)
      WRITE(3,211) (J,J=1,2)
211   FORMAT(1X,20X,I2,10X,I2)
      DO 201 I=1,2
      WRITE(3,210) I,(PLOSS(I,J),J=1,2)
210   FORMAT(1X,5X,I2,10X,F7.2,5X,F7.2,/)
201   CONTINUE
```

Figure C-5.0-1. Example Program Run Printout (Sheet 2 of 3).

```
      DO 215 J=1,2
      PTCTKT=0.0
      DO 216 I=1,2
      IF(I.EQ.J) GOTO 216
      PTCTKT=PTCTKT+PWR(I,J)/SCOUPWR(I)
216   CONTINUE
      PTCTK(J)=10.0*ALOG10(PTCTKT)
215   CONTINUE
      WRITE(3,217) (PTCTK(J),J=1,2)
217   FORMAT(1X,'TOTAL CROSSTALK',2X,F7.2,5X,F7.2,/)
      WRITE(3,219)
219   FORMAT(1X,'----------------------------------------------')
      STOP
      END
```

Figure C-5.0-1. Example Program Run Printout (Sheet 3 of 3).

APPENDIX D

BIBLIOGRAPHY ON FIBER OPTIC WAVELENGTH

DIVISION MULTIPLEXING COMPONENTS AND SYSTEMS

Ackenhusen, J. "Microlenses To Improve LED-to-Fiber Optical Coupling and Alignment Tolerance," Appl Optics, (18) (21) (Nov 1, 1979), pp 3694-3699.

Alferness, R. C. "Polarization-Independent Optical Directional Coupler Switch Using Weighted Coupling," presented at OCC '79; Fifth European Optical Communication Conference, Amsterdam (Sep 17-19, 1979).

Aoyama, K., and J. Minowa. "Low Loss Optical Demultiplexer for WDM Systems in the 0.8-μm Wavelength Region," Appl Optics, (18) (16) (Aug 15, 1979), pp 2834-2836.

Aoyama, K., and J. Minowa. "Optical Demultiplexer for a Wavelength Division Multiplexing System," Appl Optics, (18) (8) (Apr 15, 1979), pp 1253-1258.

Baack, C., et al. "Optical Transmission of 16 Digitized TV Channels," Proc OCC Fifth European Opt Comm Conf, Amsterdam (Sep 17-19, 1979), pp 2021-2023.

Barthelemy, et al. "Novel Method for Transmitting Images Through Monomode Fibers," Electron Letters, (16) (11) (May 22, 1980), pp 620-621.

Belovolov, M. I., E. M. Dianov, A. A. Kuznetsov, A. S. Svakhin, V. A. Sychugov, and T. V. Tulaikova. "Optical Demultiplexer With a Glass Slide," presented at IOOC '81, Third International Conference on Integrated Optics and Optical Fiber Communication, San Francisco (Apr 27-29, 1981).

Belovolov, M., et al. "Prototype Fiber Optical Communication Line With Spectral Multiplexing in the 1.3 μm Region," Sov T. Quantum Electron, (9) (11) (November 1979), pp 1673-1675.

Botez, D., and G. Herskowitz. "Components for Optical Communications System - A Review," Proc IEEE, (68) (6), pp 689-731.

Brain, M. "Comparison of Available Detectors for Digital Optical Fiber Systems for the 1.2-1.55 μm Wavelength Range," Proc CLEO, '81, Washington, D.C. (Jun 10-12, 1981), 54.

Campbell, J. C., T. P. Lee, A. G. Dentai, and C. A. Burrus. "Dual-Wavelength Demultiplexing InGaAsP Photodiode," Appl Phys Ltr, (34) (6) (Mar 15, 1979), pp 401-402.

Campbell, J. C., A. G. Dentai, T. P. Lee, and C. A. Burrus. "Improved Two-Wavelength Demultiplexing InGaAsP Photodetector," IEEE Jnl Quantum Elec, (QE-16) (6) (June 1980), pp 601-603.

Campbell, L., and A. Barnhart. "Fiber Optic Transmission Link Analysis," SPIE, Fiber Optics for Communications and Control, (224) (1980), pp 12-18.

Case, S. K. "Pattern Recognition With Wavelength-Multiplexed Filters," Appl Optics, (18) (12) (Jun 15, 1979), pp 1890-1894.

Chang, M. B., and E. Garmire. "Monolithically Integrated Lasers and Amplifiers Using a Cleaved Substrate Technique," Integrated and Guided Wave Optics Proceedings, '80.

Conradi, J., R. Maciejko, J. Straus, I. Few, G. Duck, W. Sinclair, A. J. Springthorpe, and J. C. Dyment. "Laser Based WDM Multichannel Video Transmission System," Elec Ltr, (17) (2) (Jan 22, 1981), pp 91-92.

Dalgleish, J. F. "Splices, Connectors, and Power Couplers for Field and Office Use," Proceedings of IEEE, (68) (10) (October 1980).

Dewitt, R. G., and G. H. Edwards. "Exploiting the Present and the Future (Fibre Optic Telephone System)," Telephony, (198) (10) (March 1980), pp 30-31, 35-36, 41-42.

Dragon, R. E. "Wavelength Division Multiplexing System Applications," Proceedings Southcon '82, Session 9, Fiber Optic Communications System.

Elion, H. A. "Recent Developments in Wavelength Division Multiplexing," Proceedings of 2nd International Fiber Optic and Communications Exposition (September 1979).

Ettenberg, W., and G. Olsen. "Diode Lasers for the 1.2 to 1.7 Micrometer Range," Laser Focus (March 1982), pp 61-66.

Flanagan, M. "Color Multiplexing on an Optical Fiber," Electro-Optical Sys Des, (11) (3) (March 1979), pp 31-36.

Fujii, Y., K. Aoyama, and J. Minowa. "Optical Demultiplexer Using a Silicon Echelette Grating," IEEE Jnl Quantum Electron, (QE-16) (2) (February 1980), pp 165-169.

Fujii, Y., et al. "Optical Switching Network for Optical Fiber Communications," Proc OCC '79, Amsterdam (Sep 17-19, 1979), pp 1332-1335.

Fukuzawa, T., and M. Nakamura. "Mode Coupling in Thin-Film Chirped Gratings," Optical Ltr, (4) (11) (November 1979), pp 343-345.

Funahashi, T., and Y. Fukuchi. "An Experiment in Four Channel Video Signals Transmission Using Dual Wavelength Division Multiplexer Technique With a Single Optical Fiber," FOC '81 West; Fiber Optics and Comm Proc, San Francisco (Sep 1-3, 1981), pp 139-143.

Game, H. "Japan's Progress in Diode Lasers," Laser Focus, (March 1982), pp 57-59.

Gasparian, G., and A. R. Nelson. "Technical Proposal for Optical Wavelength Multiplexers," ITT EOPD (May 2, 1980).

Gravel, R., and A. R. Nelson. "A Symmetrical Star Coupler for Optical Fiber System," Appl Optics, (20) (15) (Aug 1, 1981), pp 2735-2737.

Hashimoto, K., and K. Nosu. "Low-Loss Optical Multi/Demultiplexer Using Interference Filters," Proc OCC '79, Fifth European Opt Comm Conf, Amsterdam (Sep 17-19, 1979), pp 1151-1159.

Hill, A. M. "Practical Constraints on Wavelength Multiplexing of Multimode, Digital Systems in the 850 nm Region," Proceedings of the Optical Communications Conference, Amsterdam (Sep 17-19, 1979).

Hill, K., B. Kawaski, and D. C. Johnson. "Efficient Power Combiner for Multiplexing Multiple Sources to Single Fiber Optical System," Applied Physics Letters, (31) (11) (Dec 1, 1977), pp 740-742.

Horner, J. L., and J. E. Ludman. "Holographic Optical Element (HOE) for Demultiplexing in Fiber Optic Systems," Recent Advances in Holography, SPIE, (215), Los Angeles (Feb 4-5, 1980).

Horner, J. L., and J. E. Ludman. "Single Holographic Element Wavelength Demultiplexer," Appl Optics, (20) (10) (May 15, 1981), pp 1845-1847.

Horsley, A. W., and E. S. Usher. "Optical Fiber Communication Systems in PTT Networks," Elec Comm (GB), (55) (4) (1980), pp 268-275.

Ichida, et al. "Bidirectional Video Transmission System Using a Single Optical Fiber," Proc OCC '79; Fifth European Opt Comm Conf, Amsterdam (Sep 17-19, 1979), pp 2031-2036.

Ih, C. S. "Characteristics of and Requirements for Subnanometer-Wavelength Multiplexing," Proceedings of IOOC '81, Third International Conference on Integrated Optics and Optical Fiber Communication, New York (1981), pp 66-68.

Ishikawa, S., K. Takahashi, and K. Doi. "Wavelength Division Multiplexers/Demultiplexers," NEC Res Dev (October 1980), pp 65-71.

Ishio, H., and T. Miki. "A Preliminary Experiment on Wavelength Division Multiplexing Transmission Using LED," Technical Digest 1977 International Conference on Integrated Optics and Optical Fiber Communication, Tokyo, Japan, (C7.3) (July 1977), pp 493-496.

Ishio, H. "Wavelength Division Multiplexing Transmission Technology," Proceedings of the Optical Communication Conference, Amsterdam (Sep 17-19, 1979).

Ito, K., et al. "Bidirectional Fiber Optic Loop-Structured Network," Electronic Letters, (17) (2) (Jan 22, 1981), pp 84-85.

Iwano, T. "On the Commercialization of Optical Fiber Bidirectional Transmission Equipment Using LED and WDM Techniques," IEEE Conf Proc (1980), pp 3851-3854.

Johnston, A., and L. Bergman. "Application of Fiber Optics in Spacecraft," SPIE, Fiber Optics for Comm and Control, (224) (1980), pp 76-83.

Kajiyama, K., S. Hata, and Y. Mizushima. "Au-Diffused pin Photodetector Designed for Frequency Multiplexing Optical Fiber System," IEEE Trans Elec Devices, (ED-24) (9) (September 1977), pp 1192-1193.

Karney, J. "Performance of High Bandwidth Multichannel Fiber Optic Link Utilizing Wavelength Multiplexing," SPIE, Infrared Fibers, (266) (1981), pp 56-59.

Killai, U., C. Clauseu, and G. Rabe. "Binary Phase Gratings for Couplers Used in Fiber Optic Communications," Fiber and Integrated Optics, (3) (2.3) (1980), pp 221-233.

Kimura, T., and K. Daikokur. "A Proposal on Optical Fiber Transmission Systems in a Low Loss 1.0-1.4 μm Wavelength Region," Optical and Quantum Electronics, (9) (1977), pp 33-42.

Kincaid, B. E. "Advanced Fiber Optic Systems for Avionics Applications," Proceedings of Digital Avionics Systems Conference, New York (1981), pp 507-513.

Kobayashi, K., and M. Seki. "Microoptic Grating Multiplexers and Optical Isolators for Fiber Optic Communications," IEEE Jnl Quantum Elec, (QE16) (1) (January 1980), pp 11-22.

Kobayashi, M., and H. Terui. "Optical Demultiplexer Using Coupling Between Nonidentical Waveguides," Appl Optics, (17) (20) (Oct 15, 1978), pp 3253-3258.

Kobayashi, K., R. Ishikawa, and S. Sugimoto. "Micro-Optic Devices for Fiber-Optic Communications," Fiber Integrated Optics, (2) (1) (1979), pp 1-17.

Koester, W., and F. Mohr. "Bidirectional Optical Link," Electrical Communication, (55) (4) (1980).

Kremers, E., et al. "A 280 Mb/s Fiber Optic Communications Link," Proc of OCC '79 - Fifth European Optical Communications Conference, Amsterdam (Sep 17-19, 1979), pp 2221-2223.

Ladany, I., and J. M. Hammer. "Single-Mode Laser Studies: (I) Design and Performance of a Fixed-Wavelength Laser Source and (II) Coupling of Lasers to Thin-Film Optical Waveguides," NASA Contract Report 3341 (October 1980), 61.

Laude, J. P., J. Flamand, and J. M. Lerner. "Diffraction-Limited Wavelength Multiplexers/Demultiplexers - A New Approach," presented at IOOC '81, Third International Conference on Integrated Optics and Optical Fiber Communication, San Francisco (Apr 27-29, 1981).

Lauer, B., and J. Schleefer. "LEDs or DLs: Which Light Source Shines Brightest in Fiber-Optic Telecommunications Systems," Electronic Design, (8) (1980), pp 131-135.

Lee, T. P., J. C. Campbell, A. G. Dentai, and C. A. Burrus. "Dual Wavelength Demultiplexing InGaAsP/InP Photodiode," presented at Optical Fiber Communication Conference, Washington, D.C. (Mar 6-8, 1979).

Lee, T., C. Burns, and A. Denton. "Dual Wavelength Surface Emitting InGaAsP LEDs," Elec Ltr, (16) (22) (Oct 23, 1980), 865.

Lee, T. P. "Recent Development in Light-Emitting Diodes (LEDs) for Optical Fiber Communications System," SPIE, Fiber Optics for Communications and Control, (224) (1980), pp 92-101.

Lombarde, R. "Versatile Fiber Optic Multiplexer," FOC '81 West - Fiber Optics and Communications Proc, San Francisco (Sep 1-3, 1981), pp 53-55.

Lyndin, M., et al. "Four Channel Integrated Optics Couplers and Frequency Channel Multiplexer," Sov T. Quantum Electron, (10) (1) (January 1980), pp 75-78.

Mahlein, H. F. "Designing of Edge Interference Filters for Wavelength-Division Multiplex Transmission Over Multimode Optical Fibers," Siemens Forsch Entwicklungsber Res Dev Rep, (9) (3) (1980), pp 142-150.

Mahlein, H. F., H. Michel, W. Rauscher, A. Reichelt, and G. Winzer. "Interference Filter All-Fibre Directional Coupler for WDM," Elec Ltr, (16) (15) (Jul 17, 1980), pp 584-585.

Metcalf, B., and C. Kleekamp. "Designer's Guide to Fiber Optics, III," EDN, (23) (4) (Feb 20, 1978), pp 61-68.

Metcalf, B. D., and J. F. Frevidokes. "High Capacity Wavelength Demultiplexer With a Large Diameter Grin Rod Lens," Appl Optics, (21) (5) (Mar 1, 1982).

Metcalf, B. D., et al. "Wavelength Division Multiplexing Incentives and Technical Viability," Proceedings - Southcom '82, Session 9, Fiber Optic Communications System.

Mikes, T. "Wavelength Division Multiplexing: What It Could Do," Optical Spectra, (15) (3) (March 1981).

Mikey, T. "Plane Holographic Diffraction Gratings - Current Status," Canadian Journal of Spectroscopy, (25) (5) (1980), pp 41A-43A.

Miki, T., and H. Ishio. "Viabilities of the Wavelength Division Multiplexing Transmission System Over an Optical Fiber Cable," IEEE Trans Comm, (COM-26) (7) (July 1978), pp 1082-1087.

Miskovic, E., and D. Alford. "Wavelength Stabilization Techniques for WDM Laser Transmitters," FOC '81, Fiber Optics and Communications Proc, San Francisco (Sep 1-3, 1981).

Miyanuga, S., and T. Asakura. "Intensity Profile of Outgoing Beams From Uniform and Linearly Tapered Grâting Couplers," Appl Optics, (20) (4) (Feb 15, 1981).

Miyauchi, E., T. Iwama, H. Nakajima, N. Tokoyo, and K. Terai. "Compact Wavelength Multiplexer Using Optical Fiber Pieces," Optical Ltr, (5) (7) (July 1980), pp 321-322.

Moharam, M., and T. Gaylord. "Coupled Wave Analysis of Reflection Gratings," Appl Optics, (20) (2) (Jan 15, 1981), pp 240-244.

Nagan[illegible], K., et al. "Optimizing Optical Transmitters and Receivers for Transmitting Multichannel Video Signals Using Laser Diodes," IEEE - Trans on Comm, (29) (1) (January 1981), pp 41-45.

Nelson, A. R., and D. H. McMahon. "Passive Multiplexing of Digital Fiber Optic Sensors," Appl Optics, (20) (6) (Mar 15, 1981), pp 915-916.

Nicia, A. "Lens Coupling in Fiber Optic Devices - Efficiency Limits," Appl Optics, (20) (18) (Sep 15, 1981).

Nicia, A. "Wavelength Multiplexing and Demultiplexing Systems for Single Mode and Multimode Fiber," ECOC '81.

Nishihara, H., et al. "Integrated Optical Grating Circuit Fabricated by Electron Beam Direct Writing Technique," Proc of OCC '79; Fifth European Optical Communication Conference, Amsterdam (Sep 17-19, 1979), pp 1511-1514.

Nosu, K., and H. Ishio. "A Design of Optical Multi/Demultiplexers for Optical Wavelength Division Multiplexing Transmission," Trans Inst Elec and Comm Eng (Japan), (E62) (11) (November 1979), pp 815-816.

Nosu, K., H. Ishio, and K. Hashimoto. "Multireflection Optical Multi/Demultiplexer Using Interference Filters," Elec Ltr, (15) (14) (Jul 5, 1979), pp 414-415.

Ogawa, K., et al. "System Experiments Using 1.3 μm LEDs," Elec Ltr, (17) (2) (Jan 22, 1981).

Ogle, J. W. "Spectral Equalization of High Frequency Broadband Signals Utilizing WDM Techniques," Proc of CLEO '81, Washington, D.C. (Jun 10-12, 1981).

Ormond, T. "Wavelength Multiplex, Demultiplex Devices Emerge From Fiber Optic Research," EDN, (26) (3) (Feb 4, 1981), pp 73-74.

Popov, Y. "Application of Optical Communication Lines in Computer Techniques," Technical Digest 1977 International Conference on Integrated Optics and Optical Fiber Communication, Tokyo, Japan (C7.5) (July 1977), pp 501-502.

Proebster, W., and H. Grothe. "Transparent InGaAsP/InP Luminescent Diode for Optical Multiplex Transmission Systems," presented at IOOC '81, Third International Conference on Integrated Optics and Optical Fiber Communication, San Francisco (Apr 27-29, 1981).

Rice, R. R., J. D. Zino, D. A. Bryan, E. A. Dalke, and W. R. Reed. "Multiwavelength Monolithic Integrated Fiber-Optic Terminal," SPIE Seminar Proceedings, (176), Washington, D.C. (Apr 17-18, 1979), pp 133-140.

Sakai, S., T. Aoki, Y. Amemiya, and M. Umeno. "A New InGaAsP/InP Dual Wavelength LED," Appl Phys Ltr, (35) (8) (Oct 15, 1979), pp 588-589.

Saruwatani, M., et al. "Optically Accessing Loop (OPAL) Network Using Wavelength-Division Multiplexing Technology," IEEE Conf Proc (1980), pp 2861-2865.

Scholl, F. W., K. Nakano, I. Deyhimy, and J. S. Harris. "High Speed GaAs Avalanche Photodiode," IEEE Trans Elec Devices, (ED-24) (9) (September 1977), 1203.

Sheem, S. K., and R. P. Moiller. "Single-Mode Fiber Wavelength Multiplexer," Journal of Applied Physics, (51) (August 1980), pp 4050-4052.

Soref, R. A., and M. Ross. "Multimode Switching Components for Multi-Terminal Links," SPIE, (150), San Diego (Aug 28-29, 1978), pp 142-149.

Stakelon, T. S., and R. C. Schweizer. "Optimizing the Performance of LED Wavelength Multiplexed Systems," presented at IOOC '81, Third International Conference on Integrated Optics and Optical Fiber Communication, San Francisco (Apr 27-29, 1981).

Stewart, W. "Wavelength Filtering Effects in Multimode Fibers," Proc of OCC; Fifth European Optical Communications Conference, Amsterdam (Sep 17-19, 1979), pp 1231-1234.

Subharav, W. V. "Electrical and Fibre Optic Data Links," Southcon '82 - Proceedings, Session 9, Fiber Optic Communication Systems.

Suematsu, Y. "Sources for Long Wavelength Optical Communication Systems," Proc of OCC '79; Fifth European Commercial Conference, Amsterdam (Sep 17-19, 1979), pp 211-214.

Sugimoto, S., K. Minemura, K. Kobayashi, M. Seki, M. Shikada, A. Ueki, and T. Yanase. "High Speed Digital Signal Transmission Experiments by Optical Wavelength Division Multiplexing," Elec Ltr (GB), (13) (22) (Oct 27, 1977), pp 680-682.

Sugimoto, S., and K. Kobayashi. "Optical Passive Components for Communications," presented at IOOC '81, Third International Conference on Integrated Optics and Optical Fiber Communication, San Francisco (Apr 27-29, 1981).

Takahashi, H., et al. "2 x 2 Optical Switch and Its Use," Proc of CLEO '81, Washington, D.C. (Jun 10-12, 1981).

Takeuchi, S., M. Katoh, T. Sugawa, Y. Hamasaki, M. Ikeuchi, and S. Iguchi. "Optical Directional Filter and Its Application to the Bidirectional Transmission System," Proceedings of the Optical Communication Conference, Amsterdam (Sep 17-19, 1979).

Tamir, T., and K. C. Chang. "Analysis and Design of Blazed Dielectric Gratings," Integrated and Guided Wave Optics, Proceedings '80.

Tanaka, T., H. Serizawa, and Y. Tsujimoto. "Simple Structure High Isolation Multi/Demultiplexer," Elec Ltr, (16) (23) (Nov 6, 1980), pp 869-870.

Tangonan, G., et al. "Planar Multimode Devices for Fiber Optics," Proc of OCC '79; Fifth European Opt Comm Conf, Amsterdam (Sep 17-19, 1979), pp 2151-2155.

Thelen, A. "Nonpolarizing Edge Filters," Jnl Optical Soc Amer, (71) (3) (March 1981), pp 309-314.

Thyagarajan, K., et al. "Aberration Losses of the Micro-Optic Directional Coupler," Appl Optics, (19) (2) (Jan 15, 1980), pp 266-269.

Tien, P. K., and R. J. Capik. "A Thin Film Spectrograph for Guided Waves," Integrated and Guided Wave Optics Proceedings '80.

Tomlinson, W. J. "Aberrations of Grin Rod Lenses in Multimode Optical Fiber Devices," Appl Optics, (19) (7) (Apr 1, 1980), pp 1117-1126.

Tomlinson, W. J. "Applications of Grin Rod Lenses in Optical Fiber Communication Systems," Appl Optics, (19) (7) (Apr 1, 1980), pp 1127-1138.

Tomlinson, W. J., and G. D. Aumiller. "Optical Multiplexer for Multimode Fiber Transmission Systems," IEEE Jnl Quantum Elec, (QE-13) (9) (September 1977), pp 90-91.

Tomlinson, W. J. "Wavelength Multiplexing in Multimode Optical Fibers," Appl Optics, (16) (8) (August 1977), pp 2180-2199.

Toms, N. "An Integrated Network Using Fiber Optics (INFO) for the Distribution of Video, Data, and Telephony in Rural Areas," IEEE Transcripts on Communications, (COM-26) (July 1978), pp 1037-1045.

Tsai, C. S. "Ultrahigh Data Rate Time-Multiplexed PCM Fiber/Integrated Optics Communication Systems," Proc Natl Elec Conf, (29) (October 1974), pp 381-386.

Wada, O., et al. "A New Type InGaAsP/InP DH LED/or Fiber Optical Communication System at 1.2-1.3 μm," Proc of OCC '79; Fifth European Comm Conf, Amsterdam (Sep 17-19, 1979), pp 461-466.

Wagatsuma, K., et al. "Mode Couplings in Corrugated Waveguide Optical Multiplexers," Proc of OCC '79; Fifth European Optical Communications Conference, Amsterdam (Sep 17-19, 1979), pp 1531-1534.

Watanabe, R., and K. Nosu. "New 2-Channel Multiplexer Using Polarization," Elec Ltr, (17) (3) (Feb 5, 1981), pp 133-135.

Watanabe, R., and K. Nosu. "Optical Demultiplexer Using Concave Grating in 0.7-0.9 μm Wavelength Region," Elec Ltr (GB), (16) (3) (Jan 31, 1980), pp 106-108.

Watanabe, R., K. Ohnishi, and K. Nosu. "Optical Demultiplexer Using a pin Photodiode Detector Array," Trans Inst Elec and Comm Eng, Japan, (E64) (2) (February 1981), pp 92-93.

Watanabe, R., K. Nosu, and Y. Fujii. "Optical Grating Multiplexer in the 1.1-1.5 μm Wavelength Region," Elec Ltr (GB), (16) (3) (Jan 31, 1980), pp 108-109.

Watanabe, R., Y. Fujii, K. Nosu, and T. Minowa. "Optical Multi/Demultiplexers for Single Mode Fiber Transmission," IEEE T. Quantum Electron, (17) (6) (June 1981), pp 976-981.

Watanabe, R., and K. Nosu. "Slab Waveguide Demultiplexer for Multimode Optical Transmission in the 1.0-1.4 μm Wavelength Region," Appl Optics, (19) (21) (Nov 1, 1980), pp 3588-3590.

Williams, J. C. "Wavelength Division Multiplexing (WDM) Couplers," ITT EOPD (1981).

Winzer, G., and A. Reichelt. "Wavelength-Division Multiplex Transmission Over Multimode Optical Fibers: Comparison of Multiplexing Principles," Siemens Forsch Entwicklungsber Res Dev Rep, (9) (4) (1980), pp 217-226.

Winzer, G., H. F. Mahlein, and A. Reichett. "Single-Mode and Multimode All-Fiber Directional Couplers for WDM," Appl Optics (Sep 15, 1981), pp 3128-3145.

Yamamoto, Y., and T. Kimura. "Coherent Optical Fiber Transmission Systems," IEEE, Journal of Quantum Electronics, (QE-17) (6) (June 1981), pp 919-936.

Yanagimoto, K. "Field Trials of Fiber Optic Subscriber Loops in Yokosuka," ICC '81 Proceedings.

Yen, H. W., H. R. Friedrich, R. J. Morrison, and G. L. Tangonan. "Planar Rowland Spectrometer for Fiber-Optic Wavelength Demultiplexing," Optics Ltr, (6) (12) (December 1981), pp 639-641).

Yi-Yan, A., C. D. W. Wilkinson, and P. J. R. Laybourn. "Two-Dimensional Grating Unit Cell Demultiplexer for Thin-Film Optical Waveguides," IEEE Jnl Quantum Elec, (QE-16) (10) (October 1980), pp 1089-1092.

*USGPO:1983-659-062-746